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THE DIFFERENTIATION OF THE DRIFT SHEETS OF NORTHWESTERN ILLINOIS

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THE PROBLEM

Ever since the present classification of the Pleistocene has been evolved with its five glacial stages—the Nebraskan, Kansan, Illinoian, Iowan, and Wisconsin—the drift of northwestern Illinois, west of the mapped Wisconsin, has had an uncertain status. After the important discovery of the Illinoian stage of glaciation, about three decades ago, Mr. Leverett referred the outermost drift in northwestern Illinois tentatively to the Illinoian stage of glaciation, and the next inner drift to the Iowan.[1] Subsequently the existence of an Iowan drift in the Labrador field was ignored by Mr. Leverett in at least two publications, and its existence in the Keewatin field questioned.[2] In 1908, Dr. William C. Alden carried on studies along Rock River and to the west, and reached the conclu-

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geological Survey Monograph XXXVIII* (1899), Plates VI and XII.

[2] "Weathering and Erosion as Time Measures," *American Journal of Science*, Vol. XXVII (1909), p. 351, and "Comparison of North American and European Glacial Drift Sheets, *Zeit. für Gletsch.*, Book 4 (1910), p. 248.

sion that no post-Illinoian ice sheet had invaded the territory.[1] It should be noted, however, that the area which he studied lies mainly west of that which the present author has called the Belvidere lobe. In 1913, Leverett suggested that the drift of northwestern Illinois and certain other drift in western Wisconsin and southeastern Minnesota may be a late stage of the Illinoian and a correlative of the Iowan drift in Iowa. Accordingly the name "Late Illinoian or Iowan" was proposed for such drift.[2] More recently the question was raised as to whether some of the drift south of Belvidere and east of Dixon may be the product of a greater advance of the Early Wisconsin ice than had formerly been suspected.[3] Because of this uncertain status, the drift of northwestern Illinois, particularly with reference to its age, has been the first to be restudied by the Illinois Geological Survey in its program for the re-examination of the Pleistocene of the state.

Throughout the investigation, the questions which were kept in mind were: (1) Is there but one drift sheet or more than one in northern Illinois, west of the mapped Wisconsin moraine? (2) What is the age of the drift or drifts?

MODE OF ATTACK

Information for answering these questions was sought in a careful study of the topographic expression of the drift, the composition of the drift, the stratigraphic sequence of the Pleistocene materials, the state of weathering of these materials, and the drainage changes which have occurred.

Heretofore in the gathering of Pleistocene data in this area, reliance has been placed chiefly on road cuts, railroad cuts, and stream exposures, but they are comparatively few and the data derived from these must be used with great discretion. The major-

[1] William C. Alden, "Concerning Certain Criteria for the Discrimination of the Age of Glacial Drift Sheets as Modified by Topographic Situation and Drainage Relations," *Journal of Geology*, Vol. XVII (1909), p. 695. Somewhat further data was included by Dr. Alden in "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geological Survey, Prof. Paper 106* (1918), pp. 137–60. Most of the succeeding authors have followed Alden's mapping, p. 153.

[2] "Iowan drift" (abstract), *Bulletin of the Geological Society of America*, Vol. XXIV, (1923), p. 698.

[3] *U.S. Geological Survey, Prof. Paper 106* (1918), p. 153, referring to the question raised by Leverett.

ity of these exposures occur on slopes where slopewash and deposition make their value debatable and uncertain. Many of the road cuts are also too shallow to show what is vital. It was the working principle of the present study to accept only such data in regard to depth of weathering as could be obtained on the uplands, where there is a minimum of wash, and to secure enough data, if possible, to carry conviction. In addition to examining all known exposures, borings were made with a sectional auger, $1\frac{1}{4}$ inches in diameter, to depths ranging from 2 feet to $17\frac{1}{2}$ feet. More than 500 such borings were made. The work required somewhat more than two field seasons with the aid of an assistant and an automobile. The distribution of the borings and exposures, which serve as a part of the basis of this paper, is shown in Figure 1.

GENERAL CONCLUSIONS

As a result of the studies made the following conclusions were reached.

1. There are at least two distinct drift sheets in northwestern Illinois, west of the Marengo Ridge and north and west of the Bloomington moraine. The uppermost drift in southern Boone, northern DeKalb, eastern Ogle, and southeastern Winnebago counties was deposited at a much later time than the drift in the area to the west. This area (see Fig. 2) has been called the Belvidere lobe after the town of Belvidere, immediately south of which the drift is well displayed.

2. The drift west of the Belvidere lobe is truly Illinoian in age, while that of the Belvidere area is Early Wisconsin in age. The boundary between the two is radically different from the old Iowan-Illinoian boundary.

3. A post-Illinoian ice sheet invaded the Green River basin, approximately to Rock Island County, depositing a thin drift which was subsequently largely buried by the outwash from the Early Wisconsin ice during the building of the Bloomington moraine and by the Rock River Valley train of Late Wisconsin age. The evidence is insufficient to determine whether this ice lobe, now called the Green River lobe, is Iowan in age or a correlative of the Shelbyville drift of Early Wisconsin age.

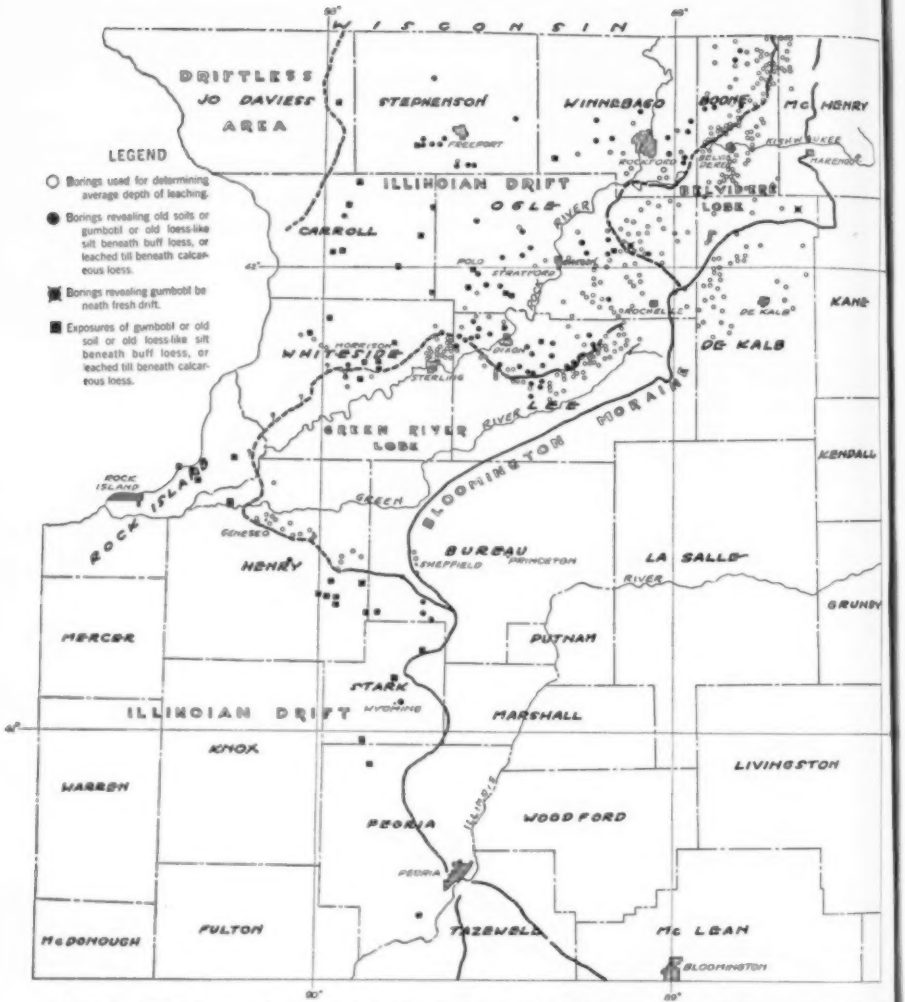

FIG. 1.—Skeletal map of northwestern Illinois showing the distribution of the borings and significant exposures involved in the present study. Scale, 1″ = approximately 30 miles.

4. The gorge of the Mississippi River below Cordova seems referable in time to the invasion of the Green River lobe, and the gorge of the Kishwaukee River and the youthful gorge of the Rock River, extending from just below the debouchure of the Kishwaukee to Byron, is referable to the invasion of the Belvidere lobe. The rest

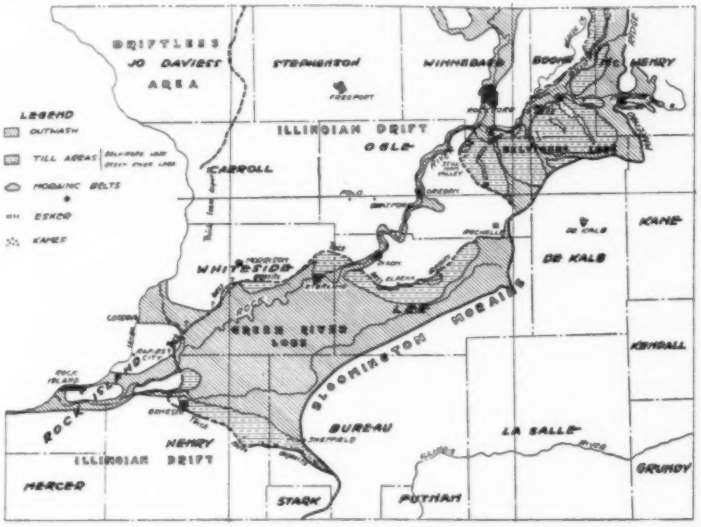

FIG. 2.—Glacial map of northwestern Illinois, showing the drift sheets and outwash deposits outside of the Bloomington moraine and the Marengo Ridge. The broken boundary lines indicate indefiniteness. Scale, 1″ = approximately 30 miles.

of the Rock River Valley, below Byron, is Illinoian and post-Illinoian in development.

A more complete account of the evidence for these conclusions will be published in a report by the Illinois Geological Survey, but it was deemed of sufficient scientific interest to give the main lines of evidence and interpretations in the present paper.

ACKNOWLEDGMENTS

The writer was greatly favored and helped by field conferences, one at the close of each of the first two seasons, by the late Professor R. D. Salisbury, of the University of Chicago, and F. W. DeWolf, Chief of the Illinois Geological Survey. Grateful acknowledg-

ment is hereby recorded. The writer also wishes to express his appreciation of the distinct service rendered by his assistants, Dr. E. P. Rothrock, of the University of South Dakota, and Messrs. George E. Ekblaw and C. P. Halushka, students at the University of Illinois.

THE BELVIDERE LOBE

Extent.—The Belvidere lobe extends as far west as Stillman Valley, Ogle County, within 4 miles of the present course of Rock River (see Fig. 2). It includes only a part of the territory which was mapped Iowan in *United States Geological Survey Monograph XXXVIII*, and its boundary transects the old Iowan area, and excludes the drumlinoid forms of northwestern Boone County which are regarded as Illinoian in age.

The ice built a curving moraine which may be traced from a point 1½ miles south of Holcomb to a point 1½ miles west of Davis Junction and thence northeast to the forks of Kishwaukee River. Some kames enter into its constitution and increase its morainal aspect. Beyond this moraine, the occurrence of relatively fresh drift, as revealed by auger borings, relatively fresh gravels as north of Stillman Valley, a smoothed aspect of the topography, and the narrow gorge of the Rock River just beyond the isolated hill at the mouth of the Kishwaukee River, indicate that the ice reached its limit some 4 miles at a maximum beyond this moraine without leaving such marginal accumulations as might be called a moraine. West and north of Belvidere and northeast of Capron there are thickened marginal deposits, but elsewhere they are poorly developed or entirely lacking. No valley trains have been identified; whether there were none originally or whether they have been buried by the alluvial back-water fill from the Late Wisconsin Valley train of Rock River and Kishwaukee River cannot be determined. Back within the area there are some well-developed knolls and ridges of fresh aspect, made up of both till and gravel. The drift is thick enough over some areas to control the major features of the topography, but near the margin the old land surface is incompletely masked. Probably the average thickness does not exceed 15 or 20 feet.

Significant phenomena.—Within the limits of the Belvidere lobe the drainage lines are poorly developed, the surface is undulating and considerable portions have a decidedly glacial aspect; the loess is thin, many crystallines and a few limestone bowlders occur on the surface, the drift materials show moderate oxidation and are leached to a shallow depth. An average of 120 borings showed 2.1 feet of soil and loess-like silt over 1.9 feet of leached till with calcareous till below, making a total of 4.0 feet of leached material (see Table I). One suggestive case of superposed tills occurs ½ mile

TABLE I

SUMMARY OF THE DATA ON LEACHING

Area	Soil	Loess-like Silt	Till	Total Average*
Bloomington drift (56 borings).....	1.1′	1.5′	1.1′	3.7′
Belvidere lobe (120 borings).....	0.9′	1.2′	1.9′	4.0′
Green River lobe (119 borings).....	1.2′	3.2′	1.3′	5.7′
Iowan drift in Iowa (146 borings)....	1.2′	0.5′	3.5′	5.2′
Illinoian drift (150 borings).....	0.9′	3.0′	4.2′	8.1′

* Of the 120 borings in the Belvidere lobe, less than 6 per cent did not pass through the leached zone; and of the 119 borings made in the Green River lobe, 4.2 per cent did not; of the 146 borings made in the Iowan drift area of Iowa, 10 per cent did not; and of the 150 borings made in the Illinoian area, 23 per cent did not.

Of the borings in the Illinoian area which showed 5 feet or less of leaching, 74 per cent occur in the headwater region of northeastern Boone County and in the Kyte River basin of Ogle County where the dissection is slight and the ground-water table high.

northwest of Irene station, where the Illinois Central Railroad cuts through the upland. Here two glacial tills are separated by fossiliferous loess and fossiliferous silts and sands with some suggestion of old vegetation, but neither the fossil content nor the vegetation excludes the possibility of a retreat and readvance of the same ice-sheet. This exposure was also observed and recorded by Leverett.[1] At or near the margin of the lobe some drainage changes occurred. The two most important ones were the diversion of the Rock River from its old course past Stillman Valley to the present gorges upstream from Byron, and the translocation of the Kishwaukee from its old course at Harrisville to the gorge across the divide east of New Milford. Two others having a bearing on the direction of ice movement will be mentioned later.

[1] *U.S. Geological Survey Monograph XXXVIII* (1898), p. 138.

Comparison with the Illinoian area to the west.—The features of the Illinoian area to the west, taken as a whole, are in considerable contrast to those just mentioned for the Belvidere lobe. The erosional topography west of Rock River is largely an inheritance of preglacial erosion, but locally there are morainic belts and postglacial gorges whose degree of erosion appears greater than that of the Belvidere lobe. The oxidation of the drift beyond the Belvidere lobe is stronger than that of the Belvidere drift, the color ranging from brown to rusty brown; the till is more compact and the upper part has a greater concentration of residual pebbles; the mantle of loess is thicker; the loess rests on the till unconformably, that is to say, the till beneath the calcareous and fossiliferous loess is oxidized and leached, whereas in the few instances in the Belvidere lobe where calcareous loess was penetrated by the auger it was found to rest on calcareous till containing limestone pebbles; gumbotil was found in a score of places in the Illinoian area, whereas no occurrence of this distinctive material is known in the Belvidere lobe except possibly at two points where the auger penetrated a gumbo-like till after passing through relatively fresh drift. (See Fig. 1 for the distribution of the exposures and borings which show this and other significant data.) Another very characteristic phenomenon of the extra-Belvidere drift is the occurrence of an old loess-like clay, 1½ to 4 feet thick, which is non-calcareous, compacted, oxidized to a brownish color, contains manganese pellets, and wherever found has a stratigraphic position between the yellow loess above and the till below. In some places this old loess-like clay contains dark organic matter as if it had formerly marked a soil horizon and supported vegetation. This was not found within the Belvidere lobe. One hundred and fifty borings in the extra-Belvidere drift showed an average of 3.9 feet of leached soil and loess and 4.2 feet of leached till over calcareous till with limestone pebbles, making a total of 8.1 feet of leached material as compared with 4 feet on the Belvidere lobe. (See Table I and also Fig. 3.) Since loess leaches more rapidly than till, it is also to be noted that the figures for the Illinoian area include a greater proportion of till than for the Belvidere lobe, and furthermore that 23 per cent of the borings failed to reach the calcareous zone in the Illinoian area, whereas only 6 per cent

failed to reach it in the Belvidere area. The average depth of leaching for the Illinoian given above is therefore something less than the actual.

Significance of these differences.—It is pertinent to inquire whether or not the differences between the Belvidere drift and the Illinoian drift can be explained on some other basis than on differences in age. That the drift is more weathered in one area than in another may be due to differences in the character of the material, or to differences in climate, or to differences in age. If the drift of the Belvidere area were composed of a tighter clay than that of the Illinoian area, such as might be derived from the belt of Maquoketa shale east of Belvidere, the leaching of the one would proceed at a less rapid rate than the leaching of the other; likewise the depth of oxidation, but less so the degree of oxidation at the surface. The geologic map of Illinois and the glacial map reveal that there is no correspondence between the belt of Maquoketa shale and the area of Belvidere drift. Besides, it is not possible on this basis to account for the difference in erosional expression of the moraines of the two areas, or the difference in degree of oxidation of the surficial portion, or the difference in concentration of the residual pebbles, or the difference in the stratigraphic relations of the buff loess, or the presence of the old loess-like silt and old soil and gumbotil in one area and not in the other. There are no differences in climate and no reasons for thinking that there have been between these two adjoining areas. A greater age for the Illinoian drift than for the Belvidere drift is the only explanation which satisfactorily explains all the facts.

The age of the drifts.—Table I summarizes the depth of leaching of various drifts, including the Belvidere drift, Bloomington drift, and Illinoian drift, based on the number of borings. Figure 3 shows graphically the differences in the depth of leaching of these drifts. All of the data indicate that the drift outside of the Belvidere Lobe is Illinoian in age. Comparing the Belvidere and Bloomington drifts, it will be seen that there is a slight difference in favor of the greater age of the Belvidere drift. But in the opinion of the writer, the major divisions of the Pleistocene cannot be made on such slight differences, and since there are Early Wisconsin moraines in

southern Illinois outside of the Bloomington, the writer prefers to correlate the Belvidere lobe with one of these, more plausibly the Champaign drift, inasmuch as the two are more nearly equivalent in the strength of their marginal expression and in the feebleness of their outwash deposits.

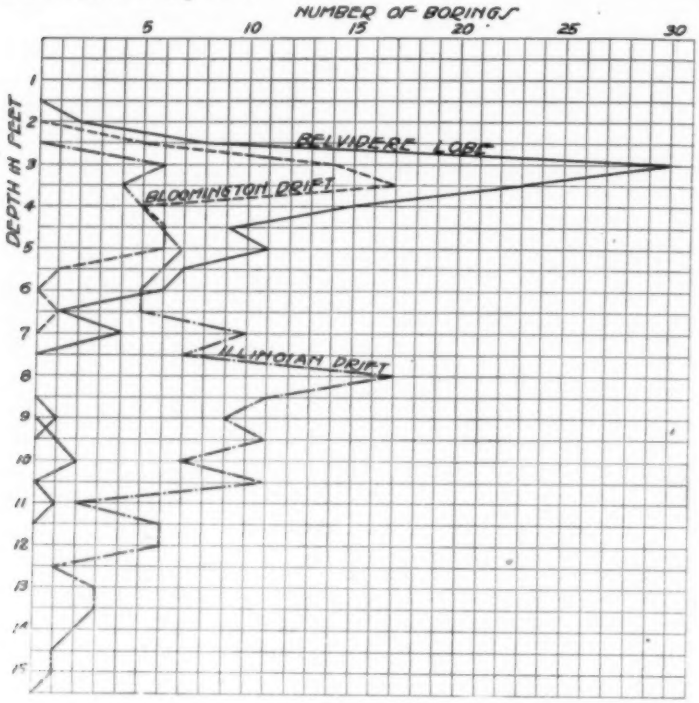

FIG. 3.—Graphs showing the number of borings recording a certain depth of leaching in the Belvidere, Bloomington, and Illinoian drift areas.

The source of the drift.—The question has been raised by Mr. Leverett, of the United States Geological Survey, as to whether or not the drift in the vicinity of Belvidere was deposited by a Green Bay lobe or by a protrusion of the Lake Michigan lobe. The presence of short morainic ridges south of the Kishwaukee River which trend northwest-southeast, offers some support to the former idea,

but there are serious objections to such an interpretation. If these ridges were the product of a southwestward-moving glacier, we should expect to find (1) the ridges represented north as well as south of the Kishwaukee River, (2) the drift of northern Boone County showing the same evidences of age as that to the south, (3) the eskers trending northeast-southwest, (4) the striae on the bedrock trending northeast-southwest, and (5) the axis of such a lobe situated to the east. Checking on these points, it should be stated that (1) there is no continuation of these ridges north of the river; (2) the drift of northern Boone County is more weathered than that south of the Kishwaukee River and in places in the northern part the drift is separated from the overlying loess by an old soil, whereas no such relationship was found in the southern part; (3) an esker-like ridge less than ½ mile long situated about 1 mile south of Cherry Valley parallels the Kishwaukee River in a northeast-southwest direction, but a much larger esker on the upland near Irene station trends at right angles to this in conformity to the supposed radial flow of the Belvidere lobe; (4) striae have been observed on the bedrock at the quarry 1 mile southwest of Belvidere trending a few degrees north of west;[1] and (5) a projection of the axis of the Green Bay lobe would place it west of this area rather than east. The axis could scarcely lie east of this area without encroaching upon the territory which would more likely be occupied by the master lobe, the Lake Michigan lobe. Unfortunately the lithology of the till lends no aid in the solution, because the formations which would be crossed by a Green Bay lobe would be the same for this locality as those crossed by the Lake Michigan lobe.

The best explanation which the writer has to offer for these ridges is that their materials were deposited in re-entrant angles and crevassed zones of a radial-spreading lobe, the crevasses on this side of the lobe trending in a northwest-southeast direction. Melting was more rapid along these crevassed zones than elsewhere and with the ice and glacial waters continually bringing material forward, greater accumulations took place here than elsewhere beneath the ice. The quantity of gravel in these ridges is in harmony with this

[1] Rollin D. Salisbury and Harlan H. Barrows, "The Environment of Camp Grant," *Illinois Geological Survey Bulletin 39* (1918), p. 44.

hypothesis. The northwestward movement of the ice on this side of the lobe is borne out by the striae at the quarry southwest of Belvidere and by the trend of the large esker. This explanation is further supported by the restriction of the morainic belts to the Belvidere lobe and their disappearance to the southeast toward the central axis of the lobe. The protrusion of the Belvidere ice lobe from the main Michigan lobe blocked the valley of Piscasaw Creek and diverted its waters temporarily westward across the divide into Beaver Creek, and later during its recession impounded the waters of Rush Creek Valley in western McHenry County until they poured across the divide into Piscasaw Creek Valley. An inspection of the Belvidere topographic map, which shows these old channels, will make it clear that their explanation would be difficult on the basis of a southwestward-moving ice.

THE GREEN RIVER LOBE

The drift of the Green River lobe is mostly buried by the outwash sand and gravel from the Bloomington moraine and the Late Wisconsin Valley train of Rock River, but strips of this drift are exposed on the north and west sides and patches in the western part (see Fig. 2). The boundary of this lobe on the north side is definite for some 3 miles west of Eldena and 10 miles to the east and north, but less so to the west. On the south side the boundary is fairly definite.[1] The western limits cannot be definitely mapped, due to the patchy character of the drift, the heavy deposits of loess and sand on the upland, and the sand and gravel outwash on the lowlands; but there is reason to think that the ice blocked the old course of the Mississippi River in northeastern Rock Island County and caused its diversion across the rock divide south of Cordova. The evidence for this will be considered later.

The strip along the north side.—From a point near the north line of Lee County and about 10 miles west of the east line, a strip of relatively fresh drift up to six miles wide extends across the upland to the southwest to a point south of Dixon, thence north of west into the area northeast and north of Sterling, and thence south of

[1] This portion of the boundary is much like that drawn by Leverett for the south side of the Iowan drift, on Plate XII *U.S. Geological Survey Monograph XXXVIII;* otherwise the present mapping is in contrast to that referred to.

west into the lowland area southeast of Morrison. The valleys of Rock River and Elkorn Creek are the chief interruptions in the continuity of the belt. A low but definite ridge of thick drift marks the margin for about 2 miles west and south of Eldena and some 8 miles to the east and north, as shown in Figure 1. To the west the boundary is much less definite than could be desired, but the weathering of the drift and the relations of the drift to the loess indicate that the line which has been drawn marks approximately the limit of a relatively young drift. Ninety-three widely distributed borings along this strip showed an average of 1.2 feet of soil, 3.1 feet of non-calcareous loess, and 1.3 feet of leached till, making a total of 5.6 feet of leached or non-calcareous material. In repeated cases where the loess was thick enough to be calcareous, the till below was found to be calcareous and to contain limestone pebbles to the top, showing that no interval of weathering intervened between the deposition of the loess and the till of this strip. North of the margin of this strip, thick loess lies unconformably on the till. That is to say, either an old soil or humus muck or old non-calcareous loess-like silt or gumbotil lies between the two, or the calcareous zone of the loess rests upon leached and oxidized till. No exposure of gumbotil is known in the belt of younger drift except at one place along the east line of the southeast quarter of Sec. 33, T. 21 N., R. 10 E., south of a low portion of the marginal moraine, where there appears to be an absence of the younger drift. In the territory immediately north of the line, the total average thickness of leached till and loess is nearly twice as great as south of the line. The writer knows of no other adequate explanation for these phenomena than difference in age. As in the case of the Belvidere lobe, there is a paucity of outwash related to the younger drift, and a corresponding lack of kames in the moraine. Southeast of Dixon the Rock River appears to have been blocked by this ice lobe, as indicated not only by relatively fresh drift northeast of Sterling but by an old channel scar skirting the margin and comparable in size to the Rock River.

The strip along the south side.—South of the Green River sand plain and extending west from the Bloomington moraine at Sheffield to Geneseo, there is another strip of drift with thin loess, which appears to be of the same age as the strip of drift along the north

side. To the south is undoubted Illinoian drift heavily overlain with loess (see Fig. 1). For 6 miles west of the Bloomington moraine, the drift laps upon the highland and is bounded on the south by a belt of kames. Farther west to beyond Geneseo the strip is mostly low-lying and the border is marked by a thick accumulation of sandy loess which is known to have a thickness in excess of 35 feet. Over the Illinoian area south from here the loess thins somewhat and becomes finer, but maintains a considerable thickness, while over the strip of drift of youthful aspect it is scanty. At one place along the border, at the edge of the thick loess,[1] a shallow road-cut exposure was found which showed fresh till with limestone pebbles overlying a loess-like deposit, which resembles the loess southward from here, and which at various places is known to rest on weathered Illinoian drift.

Twenty-six borings on the strip of relatively fresh drift revealed an average of 1.2 feet of soil, 3.5 feet of non-calcareous loess-like silt, and 1.6 feet of leached till overlying calcareous till, making a total of 6.3 feet of non-calcareous material. It will be noted that this is so nearly like that of the strip on the north side of the Green River basin that they may properly be considered to be of the same age. Reference to Figure 1 will reveal that the exposures and auger borings which show positive evidence of an unconformity between the loess and the underlying till are situated almost entirely outside of the boundary of the relatively fresh drift, on both the north and the south sides of the basin.

THE AGE OF THE GREEN RIVER LOBE

It is to be kept in mind that the evidence for the differentiation of the Green River lobe from the Illinoian drift is based not only upon differences in leaching but also upon the occurrence of gumbotil, old soils, old loess-like silts and weathered zones between the Illinoian drift and the overlying loess and the general absence of such evidences in the Green River lobe. But the depth of leaching, based upon numerous and well-distributed auger borings, affords some measure of the comparative ages of the two drifts. In Table I, it will be seen that the average depth of non-calcareous materials

[1] About the center of the south line of Sec. 30, T. 16 N., R. 6 E., Bureau County.

in 119 different borings in the Green River drift area was 5.7 feet as compared with an average of 8.1 feet in the Illinoian drift area, based on 150 borings. (See Fig. 4 for a graphical presentation of

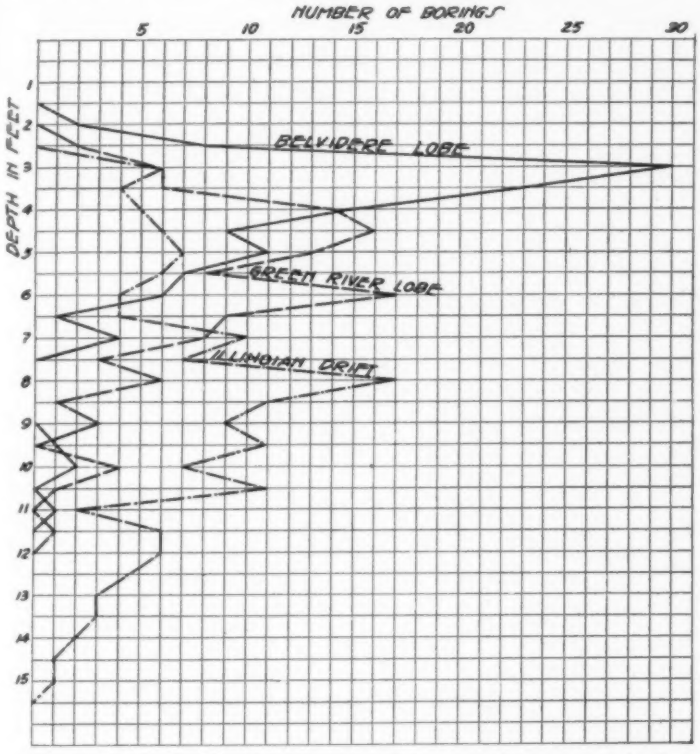

FIG. 4.—Graphs showing the number of borings recording a certain depth of leaching in the Belvidere, Green River, and Illinoian drift areas.

these data.) The average thickness of leached till is more than three times greater for the Illinoian drift than for the Green River drift, while the thickness of the overlying non-calcareous loess or loess-like silts is about the same.[1] It is also of interest to note that

[1] The thickness of the calcareous loess is not given, but it is much greater on the Illinoian than on the Green River drift; in many cases so thick that the auger failed to reach the till below, and hence such borings could not be used.

23 per cent of the 150 borings in the Illinoian area did not pass through the leached zone of the drift, while only 4 per cent failed to do so in the Green River area.

From this and the other data, there is no question in the mind of the writer but that the Illinoian drift is distinctly older than the Green River drift. The question now remains as to whether the Green River drift is Iowan or Early Wisconsin in age.

Table I gives comparative data for the leaching of the Green River drift and the Iowan drift in Iowa. The average thickness of non-calcareous materials resting upon calcareous till in the two areas is 5.7 feet for the Green River lobe and 5.2 feet for the Iowan drift. This would at first glance make it appear that the Green River drift is at least as old as the Iowan drift, but this non-calcareous zone includes thicker loess-like silt and thinner till in the former case than in the latter. Loess leaches much more rapidly than till because of its porosity and absence of pebbles, probably twice as fast according to the writer's data. If this ratio is used and the data evaluated correspondingly, the leaching of the Green River drift would compare with that of the Iowan drift in the ratio of 3.5 to 4.3, and with the Belvidere drift, 3.5 to 2.9. The data for the age of the Green River lobe are, therefore, not decisive. The Green River lobe is surrounded by thick loess, which, it is to be noted, is the same relationship as holds for the Iowan drift in Iowa.

THE TERMINUS OF THE GREEN RIVER ICE

Previous to the Green River ice invasion, the area involved was even more of a lowland than now, and invited the ice protrusion. The lowland became such in pre-Illinoian times by the erosion of the old Mississippi River and its tributaries when the master stream left its present valley near Cordova and flowed southeastward to the big bend of the Illinois River.[1] The Illinoian ice reversed the drainage to the west by way of a tributary valley, now the lower course of the Rock River, and thence over a divide to the west and south. That the Cordova gorge was not cut at this time is indicated by the

[1] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geological Survey Monograph XXXVIII* (1896), overprint of Plate VI; and "Outline of Pleistocene History of Mississippi Valley," *Journal of Geology*, Vol. XXIX (1921), pp. 615–26.

narrowness of the gorge, the rapids of the stream, and the occurrence of the Illinoian gumbotil horizon essentially to the valley wall on both sides (see Fig. 2) and high above the bottom of the gorge. If the gumbotil was developed on a plain under conditions of poor drainage, as set forth by Dr. G. F. Kay and J. N. Pearce,[1] the gorge could not have existed during Sangamon times. The diversion of the waters to this course seems to have taken place later and to be referable to the invasion of the Green River lobe. If so, the Green River ice must have reached the west side of the present Rock River Valley in northeastern Rock Island County. The loess is so thick here as to obscure all of the underlying deposits, so that there is no opportunity to trace the margin, but relatively fresh drift is exposed in patches on the east side of Rock River Valley. The cutting of the Cordova gorge must have been accomplished before the ice receded, which conclusion is consistent with the finding of small remnants of Late Wisconsin Valley train in the gorge.

[1] "The Origin of Gumbotil," *Journal of Geology*, XXVIII (1920), 89–125.

THE MINERALOGRAPHY OF THE FELDSPARS
PART II[1]

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Introduction
The Potash-Soda Series
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INTRODUCTION

Part I of this study of the feldspars[2] is an attempt to summarize our knowledge of the physical-chemistry of this group of minerals. The method of attack is that of the phase rule.

[1] Contribution from the Department of Geology, University of Rochester, Rochester, New York.

[2] H. L. Alling, *Jour. Geol.*, XXIX (No. 3, 1921), 193–294.

It is sincerely hoped that the writer has already made clear that the feldspars are solid solutions and mixtures of solid solutions of three or more end members or "minals" as it was suggested that they be called.[1] It follows that the physical properties of the feldspars are continuously varying in proportion to the change in chemical composition. To make use of these properties for identification, since they are multiple component systems, they should be plotted as surfaces and not as curves.

Here, in Part II, the subject is carried further and additional aspects which were omitted before, because of the lack of space, are presented and discussed.

As our knowledge of the feldspar group, outside of crystallography, is to a very large degree confined to the plagioclase series, about one-half of the present paper is devoted to the potash-soda series. This system includes orthoclase, microcline, albite, "barbierite," anorthoclase, perthite, etc. It is not a little surprising to find that there is much uncertainty regarding the relationships between the different members of the system, as well as the correspondence between chemical composition and physical properties. Because the physical properties, including optical behavior, are a means of determining by the microscope the actual composition, this matter is presented in detail, chiefly by the aid of diagrams. But before the relation of physical properties to the composition can be thoroughly appreciated, it is necessary to understand the thermal-diagrams of the potash-soda series. There are a number of divergent opinions regarding the thermal-diagram, hence these ideas will first receive attention.

The potash-lime, barium, and strontium-bearing feldspars are treated next. Other topics are twinning, and aventurine feldspars.

THE POTASH SODA SERIES

THE DIAGRAM OF VOGT AND WARREN

The thermal diagram of the perthite feldspars in Part I (Fig. 4, p. 221) is only an approximation at the best. It is Warren's[2]

[1] *Ibid.*, p. 218.

[2] C. H. Warren, "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 148.

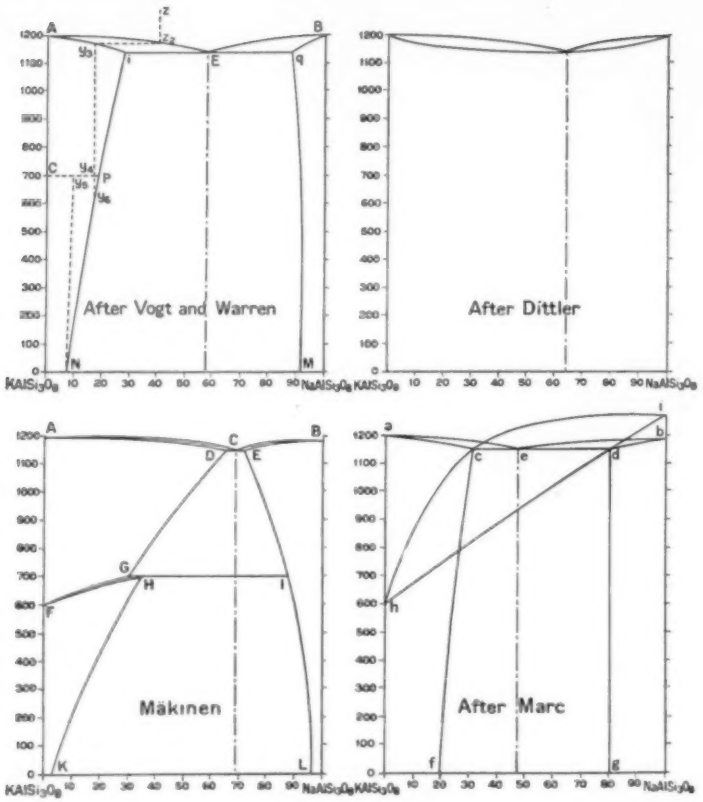


FIG. 1.—Thermal diagrams of the potash-soda feldspars after Vogt,* Warren,† Dittler,‡ Mäkinen,§ and Marc.|| These diagrams have been modified by the writer to bring them up to date, otherwise they represent the originals.

Legend for the diagram after Vogt and Warren:

A. "Melting point" of orthoclase (incongruent melting point).
B. Melting point of albite.
E. Eutectic point, 42 per cent of Or.
iN and *qM*. Boundaries of miscibilites. Solubility lines, Or and Ab.

* J. H. L. Vogt, *Tsch. Min. Petro. Mitt.*, XXAV (1905); XXV (1906); XXVII (1908).
† C. H. Warren, *Proc. Am. Acad. Arts and Sci.*, LI (No. 3, 1915), 148.
‡ E. Dittler, *Tsch. Min. Petro. Mitt.*, XXI (1912), 513.
§ E. Mäkinen, *Sonderadb. aus. Geol. Foren. Foerhandl.* XXXIX (No. 2, 1917), 121–84.
|| Robert Marc, *Chemische Gleichgewischtslehre*, p. 102.

C. Temperature horizontal, inversion of orthoclase to microcline *ipy*$_2$*N*. Solubility line when orthoclase inverts to microcline.
N. Or 92 Ab 8, approximate.
M. Or 6 Ab 94, approximate.
i. Or 72 Ab 28.
q. Or 12 Ab 88.

Legend for the diagram after Dittler:
Minimum point. Or 36 Ab 64.

Mäkinen's legend:
A. "Melting point" of orthoclase, 1190° C.
B. Melting point of albite, 1180°.
C. Eutectic point 30 per cent of Or.
DE. Miscibility gap. Solidification of the melt. Greatly exaggerated.
ADGF. Stable field of homogeneous monoclinic solid solutions (orthoclase, sanidine, and soda-orthoclase).
BEIL. Stable field of homogeneous triclinic solid solutions (albite, anorthoclase).
DEIGH. Complex, two-phase field, of monoclinic potash feldspar and triclinic soda feldspar solid solutions (orthoclase-perthite, crypto- and microperthite).
GHF. Complex, two-phase field, of monoclinic and triclinic potash feldspar solid solutions (no examples found in natural feldspars). (?)
FHK. Stable field of homogeneous triclinic potash feldspar solid solutions (homogeneous microcline).
HILK. Complex, two-phase field, of triclinic potash feldspar and triclinic soda feldspar solid solutions (microcline-perthite and antiperthite).
See text for criticism of Mäkinen's diagram.

Marc's legend:
a. Melting point of orthoclase.
b. Melting point of albite.
c. Eutectic point of monoclinic orthoclase-rich solid solution and triclinic albite-rich solid solution.
cf and *dg*. Boundaries of miscibilites. Solubility lines.
h. Transition point monoclinic $\rightleftarrows$ triclinic potash feldspars.
i. Transition point monoclinic tr $\rightleftarrows$ icilinic soda feldspars.
hdi. Boundaries of triclinic condition.
hci. Boundaries of monoclinic condition.
Interval *hcidh*. Transition interval.
Whether the transition point *i* is situated above the melting point *b* has not been determined.

modification of Vogt's[1] original (Fig. 1, Part II). It shows a eutectiferous system with the eutectic point at 42 per cent orthoclase, 58 per cent albite (plus anorthite), with inclined solubility curves.

[1] J. H. L. Vogt, "Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tsch. Min. Petro. Mitt.*, XXIV (1905), XXV (1906), and XXVII (1908).

The possibility of inversion[1] of orthoclase to microcline is not provided for in Part I, although Warren's figure introduced it. This change in modification he emphasized as a partial explanation of the formation of perthitic intergrowths.[2] The other suggested modes of origin are the "unmixing"[3] or "ex-solution"[4] of the two phases upon falling temperature and the crystallization of the eutectic. It is well to note that the diagram relates to pegmatitic feldspars only and does not apply to feldspars of other origins.

One of the difficulties with the Vogt-Warren diagram is that it was based upon chemical and quantitative microscopic studies[5] of pegmatitic feldspars at normal pressures and temperatures, and was not checked by thermal analysis. Had these data been available, it is believed that a different position of the eutectic point would have been proposed, as well as certain other conclusions drawn. The reason for this is that the proportion of the two feldspar phases in a given intergrowth depends upon the amount of exsolution that has taken place. Rapid cooling and the absence of mineralizers promote excessive undercooling and thereby retard exsolution. This condition prevails in many surface and porphyritic rocks, and hence we should not draw too general conclusions from special or local phenomena.

THE DIAGRAM OF DITTLER

Dittler[6] investigated the potash-soda series, and found that natural specimens of various composition melt between 1125° and 1200° C. either incongruently[7] or congruently, and came to the conclusion that the form of the diagram should be a series of solid solutions with a minimum.[8] (Fig. 1, Part II.)

[1] See J. B. Ferguson, *Science*, N.S., L (1919), 544–46.

[2] J. H. L. Vogt, *Tsch. Min. Petro. Mitt.* (2), XXIV, 537–41; Alfred Harker, *Natural History of Igneous Rocks*, 1909, pp. 259–260.

[3] C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, LI (1915), No. 3.

[4] The writer. See Part I, p. 222, footnote.

[5] The Delesse-Rosiwal method. See Arthur Holmes, *Petrographic Methods*, p. 313.

[6] E. Dittler, "Die Schmelzpunktskurve von Kalinatronfeldspäten," *Tsch. Min. Petro. Mitt.*, XXXI (1912), 513.

[7] See Morey and Bowen, *Amer. Jour. Sci.* (5), IV (1922), 1–22.

[8] Type III of Bachius Roozeboom.

The same conclusion was reached by Johansson[1] and Vegard.[2]

The suggestion that the diagram of the potash-soda series is a series of solid solutions with a minimum melting point, is one that Warren formerly held[3] in explanation of the homogeneity of the soda-rich phenocrysts of the porphyries in the region of the Blue Hills and Quincy, Massachusetts. Warren regarded this form of diagram as portraying the conditions prevailing at high temperatures, but with falling temperature exsolution took place. He later abandoned this view because it is not applicable to the crystallization of granites, and considered the homogeneous alkalic feldspars, such as anorthoclase, to be metastable crystallizations. It seems to the present writer that Warren in seeking a *single* diagram for the potash-soda series abandoned an idea well worth considering. If a *series* of diagrams, as later proposed, is correct, then we can retain Warren's idea as applicable to such metastable solid solutions, but not to feldspars crystallizing under plutonic conditions.

Dittler's diagram is open to the criticism that he determined the melting point interval, the area between the solidus and liquidus, by Doetler's microscopic method. Serious errors are known to be associated with this method, as pointed out by Day.[4]

The difficulty with the Dittler diagram is that it applies to rapidly cooled metastable feldspars and not to others. The suggestion is therefore offered that a diagram which combines the diagrams of Vogt and Dittler is more likely to approach the truth than either one alone.

COMBINATION OF THE TWO EXTREMES

In Part I the combination of these extremes was attempted in Figure 5 (p. 225). The two binary diagrams are shown related to each other through the degree of equilibrium, the solid solution diagram with a minimum being the unstable one, while the eutectiferous diagram represents the system when perfect equilibrium obtains.

[1] H. E. Johansson, "Om fäldspaternas sammansättning och bildnings förhållanden," *Diese Zeitschr.*, XXVII (1905), 338. This paper the writer has not seen, as it is reported by Mäkinen ("Über die Alkalifeldspäte," *Sonderabd. aus. Geol. Föreningens.*, I (1917), to occur only as a "separate" or abstract. It is not generally known.

[2] Vegard, "Die Konstitution der Mischkrystalle," *Phys. Zeitschr.*, XVIII (No. 15, 1917), 33, 93–96.

[3] C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, XL (No. 5, 1913), 317–23.

[4] A. L. Day, *Fortschr. der Min. Kryst. u. Pet.*, IV (1914), 134–37.

THE DIAGRAM OF MÄKINEN

Mäkinen, in his recent and valuable paper,[1] offers a thermal diagram that may well be considered as an intermediate diagram (such as the writer suggested in Part I, p. 225). It is perhaps to be inserted close to the front plane in the figure. Mäkinen makes the miscibility gap (Mischungslücke) line *DE* in Figure 1, Part II, very short, covering only 10 per cent composition from about 66 per cent Ab to 74 per cent Ab, which he says is greatly exaggerated. He places the eutectic point at 70 per cent albite while Vogt placed it at 58 albite.[2]

Watts[3] has made a similar suggestion that the eutectic point should be nearer to albite than Vogt placed it. Here again we must remember that artificial mixtures of natural feldspars were melted and from such thermal data the conclusions were drawn. It seems that these apparently conflicting ideas can be reconciled by stating that a *single* binary diagram is not sufficient to express the crystallization of *all* potash-soda feldspars, but that a series of diagrams is necessary, grading from a simple eutectiferous system to a system of solid solutions with a minimum. Mäkinen points out[4] that pegmatitic feldspars have a *restricted* range in composition compared with porphyritic or plutonic feldspars on the one hand, and *greater* compositional freedom than drusy and adularious[5] feldspars on the other. This can be interpreted to mean that the diagram for adularious feldspars should show a eutectiferous system with the solubility lines close to the sides, indicating very limited solubility and consequently very restricted compositional freedom. The eutectic point for adularious feldspars is not known, but a reasonable position, it seems to the writer, would be about 50 per cent albite. Thus in a three-dimensional model (Fig. 2, Part II) this eutectic at 50 per cent Ab could be connected with the minimum point of the solid

[1] Eero Mäkinen, "Über die Alkalifeldspäte," *Sonderabd. aus. Geol. Föreningens. Förhandl.*, XXXIX, H. 2 (February, 1917), 149.

[2] The variation in the position of the eutectic point may well be due to the shift brought about by metastable and labile conditions. See C. H. Gulliver, *Metallic Alloys*, 1913, pp. 165–67, and J. V. Elsden, *Principles of Chemical Geology*, 1910, pp. 114–16, 153.

[3] A. S. Watts, "The Feldspars of the New England and North Appalachian States," *U.S. Bur. Mines Bull. 92*, 1916.

[4] *Op. cit.*, pp. 132–33, fig. *A–E*, Fig. 1-3, Fig. 2, Part II.

[5] *Die Feldspäte der Adulardrusen.*

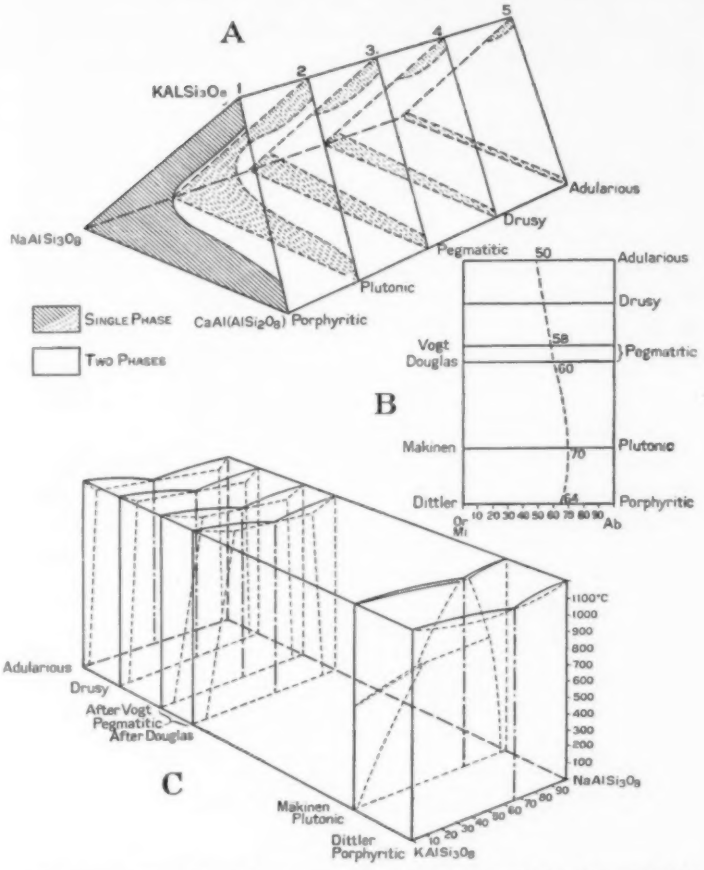


FIG. 2.—*A*. Three-dimensional compositional diagram showing fields occupied by natural feldspars of different origins. It indicates that porphyritic feldspars have a greater range in composition than those of any other origin and may even bridge the eutectic gap as sanidine and anorthoclase. It shows why sanidines may be rich in soda while adularias more closely approach the theoretical composition, $KAlSi_3O_8$. Arranged from Mäkinen's diagrams.

B. Projection of an arranged series of thermal diagrams of the potash-soda feldspars, showing possible variation in the position of the eutectic point for feldspars of different origins. This diagram is offered with full appreciation that it is based upon uncertain data.

C. Stereogram of arranged thermal diagrams of the potash-soda series showing that no *one* diagram can express the crystallization of *all* feldspars. From these diagrams the reader is to see a solid model; any transverse cross section of which is a diagram of feldspars of a particular origin.

solution diagram, having the minimum at a point about 64 per cent albite. The writer believes that Mäkinen's diagram roughly represents the conditions prevailing during the crystallization of plutonic feldspars. Douglas[1] has suggested that the eutectic point should be placed at 40 per cent orthoclase, 60 per cent albite. Such a diagram, all other matters being the same, may be, therefore, inserted in the three-dimensional model between that of Vogt and of Mäkinen. It is hoped that in spite of the many uncertainties concerning the thermal diagram of the potash-soda series, the suggestions offered in Figure 2 will be helpful in securing a proper conception of the mode of crystallization of all feldspars of this range of composition.

THERMAL STUDIES

Audley,[2] from commercial experience, says:

> The destruction by heat of the crystalline condition of a silicate does not always result in the immediate production of a homogeneous and transparent substance—that is a glass. (Potash) feldspar, for example, between 1100° and 1200° C. gives a white material resembling porcelain or devitrified glass in appearance. The feldspar has really become decomposed.

Morey and Bowen[3] have investigated this phenomenon in the Geophysical Laboratory and have shown that potash feldspar, either orthoclase or microcline, has no true melting point, that is, it melts incongruently at about 1170° C., for pure (artificial) potash feldspar, breaking up into liquid and leucite. This temperature is lowered a little with increasing amounts of other feldspar components. This necessitates the use of a binary diagram to show the thermal properties of orthoclase (or microcline) which is a binary compound of leucite and silica (Fig. 3, Part II).

$$KAlSi_2O_6 + SiO_2 \rightleftharpoons KAlSi_3O_8$$
$$\text{Leucite} + \text{Silica} \rightleftharpoons \text{K-feldspar}$$

[1] J. A. Douglas, "On Changes of Physical Constants in Minerals [by heating]," *Quar. Jour. Geol. Soc.*, LXIII (1907), 159.

[2] J. A. Audley, "Silica and the Silicates," *Van Nostrand*, 1921, p. 46.

[3] G. W. Morey and N. L. Bowen, "The Melting of Potash Feldspar," *Amer. Jour. Sci.* (5), IV (1922), 1–22.

With the above modification as to the nature of the melting of potash feldspar, the diagrams so far offered represent the present status of our knowledge.

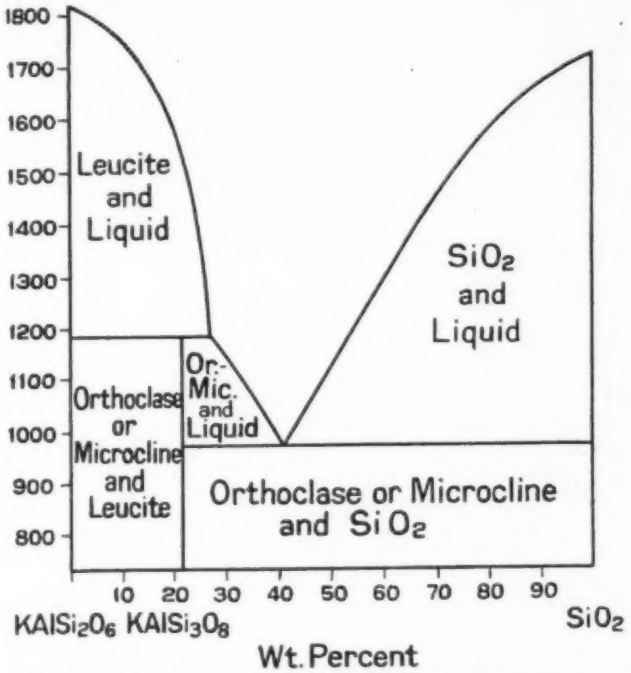


FIG. 3.—Thermal diagram of the system leucite-silica, showing incongruent melting of the intercomponent compound $KAlSi_3O_8$ (orthoclase-microcline), after Morey and Bowen. *Amer. Jour. Sci.* (5), IV (1922), 1–22.

DIMORPHISM

Orthoclase vs. microcline.—The writer, in Part I, agreed with Vogt,[1] Barbier,[2] Clarke,[3] and Harker[4] that orthoclase and microcline are dimorphous forms of the same substance. To secure evidence

[1] J. H. L. Vogt, as cited by C. H. Warren, *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 144.

[2] Ph. Barbier, "Researches sur la composition chimique de feldspaths potassique," *Bull. Soc. Franç. minéral.*, XXXI (1908), 152–67.

[3] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, 12. [4] *Op. cit.*, p. 258.

Photomicrographs of Unusual and Common Feldspars

PLATE I

All photomicrographs taken with cross nicols, ocular ×7.5, and objective, 16 mm.

A. Zonal plagioclase liparite-perlite, Pushi Hrad, Hungary. (L-91)

B. Zonal anorthoclase-crypto-microperthite in Kekequabec soda granite, Minnesota. See Grant, *Amer. Geol.*, XI (1893), 383–89, and (at present unpublished) Ph.D. thesis of Kennedy, University of Illinois (kindness of William S. Bayley). Described as an "intergrowth of albite with either soda orthoclase or soda microcline." (1150)

C 1. Adularia, St. Gottard Region, Eggerhorn, Switzerland. ($Or_{83.5}Ab_{9.5}An_{7.0}$.) Slide prepared with great care by the writer, showing phantom, incipient microcline twinning. Considered as representing inversion of orthoclase (adularia) to microcline brought about by the grinding incident to preparation of the slide. (989)

C 2. Same as *C* 1. Slide prepared by W. H. Tomlinson, probably with less care, showing greater development of phantom microcline twinning. (989 *A*)

D 1. Adularia, St. Gottard Region, Scopi, Switzerland. (Or 88 Ab 9 An 3.) Slide prepared by Tomlinson showing incipient twinning. (988)

D 2. Same as *D* 1, prepared with extreme care by the writer, showing not a trace of phantom twinning. The parallel lines are cleavage cracks. (998 *A*)

E. Crypto-microcline, pebble, Pacific Coast, phenocryst of a porphyry. (A. F. Rogers.) (Approx. $Or_{80}Ab_{18}An_2$.) The light area in the center is quartz. (1438)

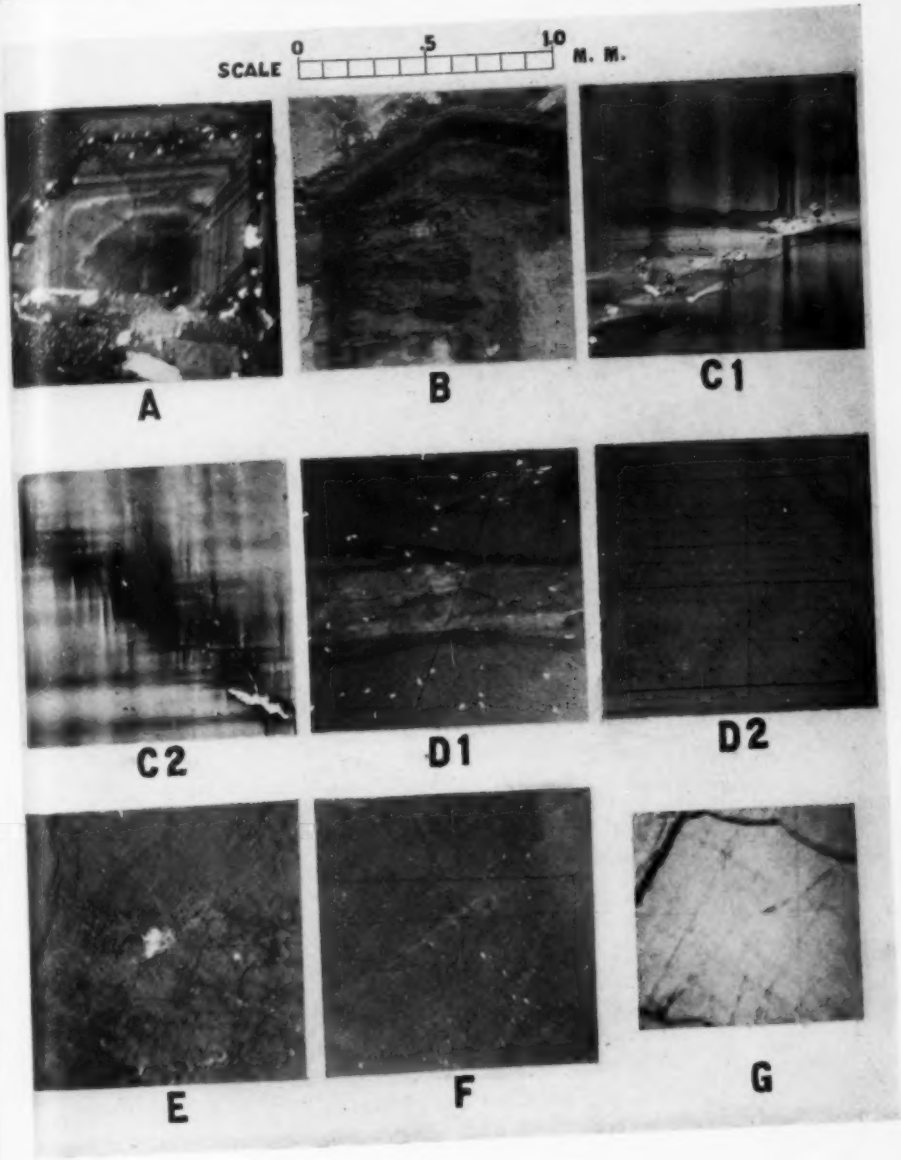
F. Moonstone ($Or_{75}Ab_{23}An_2$). Anorthoclase-cryptoperthite, from Ceylon. See Kozu, *Sci. Rept. Topoku Univ.*, Series III, Vol. I, No. 1, showing incipient development of perthite. (1394)

G. Crypto-soda microcline, sanidine, Viterbo, Italy, showing development of crypto-microcline twinning.

[1] O. Maschke, *Pogg. Ann.*, CXLV (1872), 565–68; *Weidemann's Ann.*, XI (1880), 722–34; J. L. C. Schroeder van der Kolk, *Zeitschr. f. wiss. Mikroskopie*, VIII (1892), 456–58.

[2] Pyrometric (Seger) cone determination. Hence, as Mäkinen says, only approximate.

[3] Specimen 959.


SCALE
0
.5
1.0
M. M.
A
B
C1
C2
D1
D2
E
F
G

of the true relationship between the two minerals is a very difficult matter. Since dimorphism (isomerism) is a thermal property of matter, it is reasonable to expect that the effect of "heat treatment" on natural feldspars might throw light upon this problem.

Merian and Wahl[1] through heating of fragments and thin pieces endeavored to convert microcline into orthoclase. In spite of heating to the melting point, they observed no change in the optical orientation of the specimens. Mäkinen made similar experiments which, while they throw considerable light upon the nature of anorthoclase, leave some doubt regarding the relation between microcline and orthoclase. He says[2] (in translation): "Although the expected transition (inversion) of microcline into orthoclase is indicated by these researches, still one does not dare to use this in support of the polysymmetry theory [of Groth].[3] Apparently the rate of transition is so slow and requires so long a time that it (inversion) cannot be demonstrated in the laboratory." He says that the transition from orthoclase to microcline is a "secondary"[4] process. "However, it gives no reason to assume that the final modification should be enantiotropic, i.e., that orthoclase can be transformed into microcline but not microcline into orthoclase." Morey and Bowen[5] found that there is "no appreciable difference of behavior connected with the difference in form of orthoclase and microcline," in breaking up into leucite and liquid at about 1170° C.

In Part I the results of heating the microcline-microperthite (hypoperthite) from San Diego County, California,[6] were offered on page 267, in support of inversion of orthoclase into microcline by "annealing" at about 900° C. The writer found that microclinic twinning was produced by such treatment; the amount of twinning formed being in proportion to the time the material was subjected to heat. Further study of the material has caused the writer to question the evidence. An examination of the optical

[1] A. Merian and Wahl, *Neues Jahrb. f. Min.*, I (1884), 195.

[2] Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Fören. Förhandl.*, XXXIX, H. 2 (February, 1917), 127.

[3] Paul Groth, "Chemical Crystallography" (Marshall) Wiley, 1906, 7. See Harker, *op. cit.*, p. 258; also Wahl, *Ofversikt af Finska Vet. Soc. Förh.*, L (1906–7), No. 2.

[4] In the original the word is "sekulärer," which the writer suspects is a typographical error for "sekundärer."

[5] Morey and Bowen, *Amer. Jour. Sci.* (5), IV (1922), 1–21. [6] Specimen 958.

constants leads to the conclusion that the composition was about: $Mi_{64.3}\ Ab_{28.9}\ An_{3.8}\ Qz_{3.0}$. A chemical analysis of the same material was made for the writer by H. B. Croasdale[1] with the following results:

TABLE I

HYPOPERTHITE, SAN DIEGO COUNTY, CALIFORNIA

SiO_2	.....	64.40	.....	.....	63.61	.....
Al_2O_3	.....	19.46	.....	.....	19.48	.....
Fe_2O_3	.....	0.12	.....	.....	0.08	.....
FeO	.....	0.22	.....	.....	0.22	.....
MgO	.....	0.13	.....	.....	0.11	.....
CaO	.....	0.42	.....	.....	0.51	.....
Na_2O	2.35*	2.40	2.46†	2.00*	1.96	1.92†
K_2O	14.38*	14.46	14.55†	14.70*	14.77	14.83†
H_2O	.....	0.12	.....	.....	0.15	.....
Total	.....	101.73	.....	.....	100.89	.....

* By the J. Lawrence Smith Method—H_2PtCl_6.
† By the use of $HClO_4$.

It was found when the material was recast that it was necessary to calculate an appreciable amount of "nephelite" or "carnegieite,"[2] as can be observed from Table II.

Thus it has turned out to be a very different feldspar than was formerly supposed. The presence of this component may well account for the development of twinning and for the failure to determine by *optical means* the actual composition. Carnegieite is reported to twin according to the albite and pericline laws, often simultaneously.

The heating of normal feldspars, lacking the nephelite-carnegieite component, leaves the matter of the isomerism of orthoclase-microcline in doubt, although long heating at 900° C. in some instances seemed to indicate a possible inversion of microcline into orthoclase, and long heating of orthoclase at 700° C. did produce a slight increase in the amount of twinning.

The lack of success of these thermal studies is offset by the results of plotting the values of the specific gravities of the potash-soda-lime feldspars. The data employed consist of about 80 feldspars, most of them natural, a few artificial. It is a regrettable fact that

[1] Of the Fraser Laboratories, New York City.

[2] $Na_2Al_2Si_2O_8$. H. S. Washington, *Jour. Geol.*, XVI (1908), 10; H. S. Washington and F. E. Wright, *Amer. Jour. Sci.* (4), XXVI (1908), 187, XXIX (1910), 52–70, and XXXIV (1912), 555.

more data are not forthcoming; for it is truly surprising to find that while many analyses are available, the values of the specific gravity are only occasionally given. In drawing conclusions from

TABLE II

RECAST OF HYPOPERTHITE, SAN DIEGO COUNTY, CALIFORNIA

	No. 958–1						
	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Total	Total/100
Percentage	63.70	19.24	0.41	2.35	14.30	.....	.....
Mol. ratio	1.0560	.1884	.0073	.0379	.1518	.....	.....
Or	.9108	.1518	.....	.....	.1518	84.63	84.2
Ab	.0822	.0137	.....	.0137	.....	7.20	7.1
An	.0146	.0073	.0073	.....	.....	2.04	2.0
Ne	.0484	.0242	.....	.0242	.....	6.89	6.7
Total	.....	.....	.....	.....	.....	100.76	100.0
	No. 958–2						
Percentage	63.61	19.48	0.51	1.96	14.77	.....	.....
Mol. ratio	1.056	.1905	.0091	.0316	.1568	.....	.....
Or	.940	.1568	.....	.....	.1568	87.47	86.5
Ab	.0519	.0086	.....	.0086	.....	4.55	4.5
An	.0182	.0091	.0091	.....	.....	2.53	2.5
Ne	.0459	.0229	.....	.0229	.....	6.53	6.5
Total	.....	.....	.....	.....	.....	101.08	100.0

AVERAGE

	Per Cent
Orthoclase or Microcline	85.35
Albite	5.80
Anorthite	2.25
Nephelite	6.60
	100.00

such miscellaneous data we must remember that the chemical analyses of today are vastly superior to those collected and published by Dana, Hintze, Doelter, Herzenberg and others.[1] The chemical analyses were recast into terms of three components,

[1] See H. S. Washington and H. E. Merwin, *Amer. Jour. Sci.* (5), I (1921), 20. Larsen says (*U.S. Geol. Surv. Bull. 679* [1921], p. 6): "Much further work on the optical constants and more complete and accurate data on nearly all the minerals are needed . . . . a highly accurate determination of physical properties [etc.] of a mineral is of comparatively little value unless the data obtained are definitely tied to a chemical analysis." See Arthur Holmes, *Petrographic Methods and Calculations.*

K-, Na-, and Ca- feldspars. If the sum of the three feldspars was appreciably below or above one hundred, the analysis was considered inferior, or the specimen abnormal, and it was consequently omitted. Thus there has been some selection of the available data by elimination. Upon a triangular base each recast analysis was located according to the composition and indicated by a point. On each point a pin, whose length (height) represented the value of the specific gravity, was erected. In this manner a "peg model" was constructed. It is very evident from the model, or three-dimensional graph, that there are two groups, one set of pins being longer, standing higher, than the other group. As the majority of the pins giving the values of specific gravities of feldspars called in the literature "orthoclase" are longer than those called "microcline," the obvious interpretation is that orthoclase, soda orthoclase, "monoclinic" anorthoclase, as well as orthoclasic phases in perthitic feldspars, are heavier than the microclinic equivalents of these. This idea was suggested in Part I (Fig. 6, p. 228) but the writer, through the construction of the peg model, feels that such an interpretation can now be entertained with more confidence.

A single and constant physical or chemical difference between orthoclase and microcline is sufficient to establish a case of dimorphism. Apparently here the specific gravities furnish the desired evidence.

The relation of specific gravity to composition is taken up in detail later.

Albite and "barbierite."—Barbier,[1] Prost,[1] Clarke,[2] Shaller,[3] and others have reached the conclusion that there is a monoclinic modification of the soda component which the latter named barbierite. A chemical analysis of the "barbierite" from Kragerö, Norway, is as follows:

SiO_2	67.00
Al_2O_3	19.12
CaO	0.78
K_2O	1.15
Na_2O	11.74
	99.79

[1] Barbier and Prost, "Sur l'existence d'un feldspath sodique monoclinic isomorphe de l'orthoclase," *Bull. Soc. Chem.*, III (1908), 894.

[2] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, 35.

[3] W. T. Shaller, *Bull. Soc. Min.*, XXXIII (1910), 320; *Zeitschr. f. Kryst.*, L (1911), 347; *Jour. Wash. Acad. Sci.*, I (1911), 177; *U.S. Geol. Surv. Bull. 509* (1912), p. 40; Barbier and Gonnard, *Bull. Soc. Min.*, XXXIII (1910), 81.

An attempted recast results in the absurd sum of 109.69 per cent for the total feldspar and a deficiency of 7.49 per cent SiO_2 and 1.21 per cent Al_2O_3, as is shown in Table III:

TABLE III

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	Total
Percentage	67.00	19.12	0.78	1.15	11.74	99.79
Mol Wt	60.3	102.2	56.07	94.2	62.0	.....
Mol ratio	1.112	.1870	.0139	.0122	.1894	.....
K-feldspar	.0732	.0122	.....	.0122	.....	6.82
Na-feldspar	1.1364	.1894	.....	.....	.1894	99.56
Ca-feldspar	.0278	.0139	.0139	.....	.....	3.31
Total	1.2374	.2155	.0139	.0122	.1894	109.69
Deficiency	.1254	.0185	.....	.....	.....	.....
Percentage	7.49	1.21	.....	.....	.....	.....

Mäkinen[1] has already questioned the value of this analysis when he says (in translation): "The occurrence of a monoclinic sodium feldspar was recently regarded by Barbier and Prost as proved because they found a so-called monoclinic feldspar from Kragerö which contains 11.74 per cent Na_2O, 0.78 per cent CaO, and only 1.15 per cent K_2O. The sum of K_2O+Na_2O+CaO, over against SiO_2 and Al_2O_3 is still altogether too low and their analysis is to such a degree defective that they themselves can scarcely regard it as satisfactory." It is of course quite possible that their analysis is indeed defective, but when the possibility is considered of nephelite-carnegieite being present, then the results of recasting are understandable as in Table IV:

Still there is room for improvement. Can it be that the presence of hexagonal nephelite in a soda-rich feldspar to the extent of nearly 9 per cent renders the whole monoclinic, *without the possibility of any dimorphism of* $NaAlSi_3O_8$*?* Possibly. The writer is unable to offer any suggestion that bears on this question.

The writer endeavored to secure from Dr. Schaller[2] definite information regarding barbierite. Dr. Schaller reported[3] that the

[1] Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Fören. Förhandl.*, XXXIX, H. 2 (February, 1917), 122.

[2] Through Mr. English of Ward's Natural Science Establishment.

[3] August 8, 1918.

PLATE II

A. Microcline-microperthite (hypoperthite), (approx. $Mi_{60}Ab_{37}An_2Hem_1$). Sunstone, Delaware County, Pennsylvania. White areas, albite ($Mi_2Ab_{97}An_1$). Dark areas, soda microcline ($Mi_{80}Ab_{17}An_3$), showing a coarse type of intergrowth. (974)

B. Nephelite bearing anorthoclase, chesterlite ($Or_{42}Ab_{45}An_3Ne_{10}$). Poor House Quarry, Chester County, Pennsylvania, showing queer type of wavy extinction.

C. Microcline-microperthite near Unionville, Chester County, Pennsylvania (approx. $Mi_{57}Ab_{34}An_5Qz_4$), showing irregularly bordered albite spindle (bleb) in microcline. (996)

D. Microcline-microperthite (hypoperthite) from pegmatite of Yonkers gneissoid granite, Valhalla, New York, a typical pegmatitic feldspar.

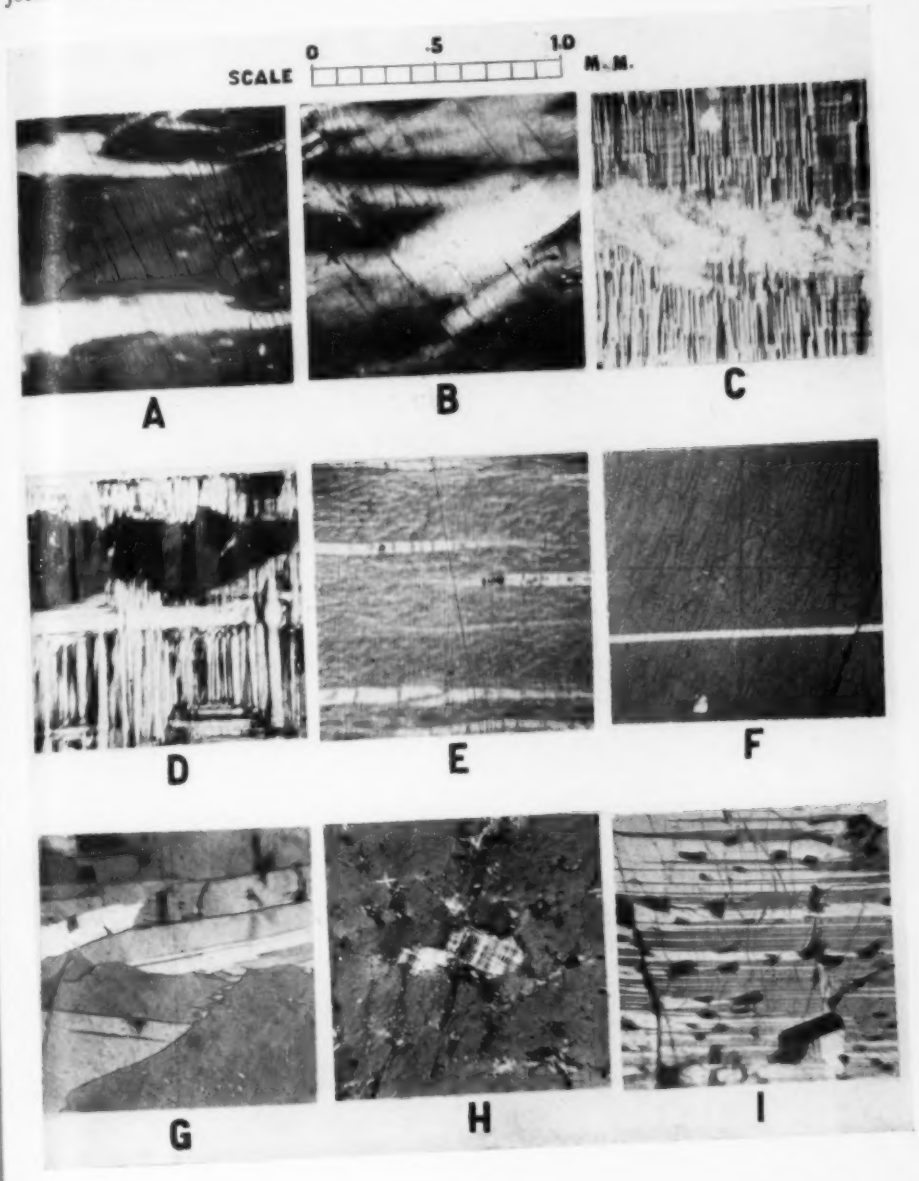
E. Cassinite, Blue Hill, 2 miles north of Medina, Delaware County, Pennsylvania. Long, thin spindles of albitic plagioclase (approx. $Mi_4Ab_{90}An_3Cn_3$) in hyalophane (approx. $Or_{76}Ab_{11}An_1Cn_{12}$). Note the small blebs of "secondary" origin giving a "grained" appearance to the whole. (Kindness of Dr. S. G. Gordon.) (1437)

F. Bytownite ($Mi_{3\cdot0}Ab_{24\cdot7}An_{73\cdot3}$), Crystal Bay, Minnesota. The white bar is a twinning striation, otherwise the slide is devoid of twinning of any kind. Unless extinction angles or indices of refraction are noted it may well be mistaken for "orthoclase." (969)

G. Albite (approx. $Or_7Ab_{83}An_2Ne_8$) from Kragerö, Norway. Possibly the so-called "barbierite," showing coarse albite twinning. (Kindness of Dr. Olaf Andersen.) (1123)

H. Potash oligoclase, Risör, Norway ($Mi_{7\cdot30}Ab_{73\cdot65}An_{19\cdot05}$), showing bleb of soda microcline (center) in slightly weathered untwinned oligoclase. (Kindness of Dr. Olaf Andersen.) (1122 *b*)

I. Granite feldspar, Adirondacks, Ausable Quadrangle near Ausable Forks, Essex County, New York (quarry near Stickney Bridge), consisting of potash feldspar blebs (approximately $Or_{85}Ab_5An_{10}$), dark areas, in Labradorite ($Mi_5Ab_{40}An_{55}$), striated plagioclase. (1096)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small specimen received from Professor Barbier verified his optical determinations, but was returned before any chemical tests could be made. Dr. Olaf Andersen sent the writer a specimen labeled "albite" from Kragerö, Norway. This proved to be a peculiar feldspar (see Plate II, *G*). The indices are: alpha, 1.527; beta, 1.534; gamma, 1.537. These agree well for albite, $Ab_{98}An_2$. The extinction angles, however, failed to be commensurate with the

TABLE IV

SECOND RECAST OF BARBIERITE

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	Total
Percentage	67.00	19.12	0.78	1.15	11.74	99.79
Mol ratio	1.112	.1870	.0139	.0122	.1894	
K-feldspar	.0732	.0122		.0122		6.82
Na-feldspar	.9840	.1580			.1580	83.11
Ca-feldspar	.0278	.0139	.1039			3.31
Nephelite	.0628	.0314			.0314	8.93
Total	1.1118	.2155	.0139	.0122	.1894	102.17
Excess	.0002					
Deficiency		.0285				
Percentage	.01	2.92				

values of the indices. (001):1.4°;[1] (010):23.9°.[1] Thus it is quite possible that this is a nephelite bearing albite of the following approximate composition: $Or_7Ab_{83}An_2Ne_8$.

Foerstner's[2] investigations of the anorthoclases of the island of Pantelleria took the form of measuring their physical properties at various temperatures. He reached the conclusion that the potash-soda feldspars constituted *two* series, one asymmetric and the other monosymmetric. "Both of these [systems] under consideration show isodimorphism of the corresponding alkali silicates [$KAlSi_3O_8$ and $NaAlSi_3O_8$], first emphasized by Professor P. Groth, one 'molecule' being in stable and the other in labile[3] equilibrium. A

[1] Determined by using the biquartz wedge after Wright.

[2] H. Foerstner, "Über künstliche physikalische Veränderungen der Feldspäte von Pantelleria," *Zeitschr. f. Kryst.*, IX (1884), 333.

[3] It seems to the writer that "metastable" is preferable to "labile." See G. H. Gulliver, *Metallic Alloys*, 1913, 164–65. Also Miers and Isaac, *Jour. Chem. Soc.*, LXXXIX (1906), 413; *Proc. Roy. Soc.*, LXXIX, A (1907), 322; *Phil. Trans.*, CCIX, A (1909), 337.

mixture of both of them, accordingly, tends to adjust itself to the final static molecular state. Inability to attain this [condition] is caused by the overpowering influence of the additional isomorphous constituents."[1]

He shows that through the proper physical means this molecular overbalance can be broken up. He believed that it was perfectly possible to change triclinic feldspar into a monoclinic form by heating, and vice versa by cooling. This can be explained, as Mäkinen points out, by dimorphism and not by Groth's theory of polysymmetry. It must be remembered, however, that most of these physical properties are measured upon the cold specimen, and such observations may or may not apply to heated feldspar.

Here the matter of the dimorphism (and isomerism) of both the potash and soda feldspars rests.

Thermal diagrams and dimorphism.—Various investigators have suggested diagrams that indicate the possible dimorphism of $KAlSi_3O_8$. It is not necessary to discuss them all in detail. A satisfactory conception can be obtained by examining the accompanying diagrams (Fig. 1, Part II). These have been modified more or less in detail by the writer to bring them up to date; the main facts, however, remain.

Warren[2] has modified Vogt's original diagram to indicate the inversion of orthoclase into microcline. This is shown by the line *Cp* in Figure 1. It will be seen that it interrupts the solubility line *iN* in that microcline is less able to dissolve the soda feldspar component. The consequences of this, as Warren points out, are that many perthitic intergrowths are due to exsolution caused by the decrease in solubility of the soda phase in the potash component on its inversion. According to the diagram orthoclase and microcline cannot exist together in equilibrium over any range in temperature. Whether they can or cannot exist in this manner in nature it is impossible at present to say. Although Mäkinen[3] says that "no examples [are] found in natural feldspars" the writer in Part I listed an adu-

[1] H. Foerstner, *op. cit.*, p. 348.

[2] C. H. Warren, "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (No. 3, 1915), 127, 154.

[3] *Op. cit.*, p. 149.

laria from Eggerhorn, Switzerland,[1] as "in the process of inverting from soda orthoclase to soda microcline" in view of the two sets of extinction angles and the variability of the microclinic twinning. Since that time several additional feldspars have been found that apparently exist in this transitional stage, although it is quite likely that such feldspars are metastable systems and not in equilibrium. Foerstner[2] has already suggested the possibility that certain anorthoclases are mixtures of the two series, "monoclinic" and "triclinic," and hence are representatives of "transitional" feldspars.

Thus it may be seen that there are two general ideas expressed by these diagrams. First, that of Warren, where the dimorphism is shown by a single line (*Cp*), and second, by Mäkinen by an area, a spherical triangle, *FGH*.

As the writer understands Warren's diagram, the solubility line *iN* holds when orthoclase does not invert (transform) to microcline. In the event of this change in modification, ipy_5N graphically indicates the decrease in solubility. These two possibilities are combined in a single diagram which may be confusing, unless this duality is kept in mind.

Harker[3] has given a diagram showing changes during cooling in a binary system where limited solubility prevails in the solid state and where one component inverts to a lower temperature form. While Harker did not state in definite terms that this illustrated the behavior of the potash-soda series of feldspars, he believed that it can be so regarded if a single line conception is entertained.

The suggestion of Mäkinen, that the transformation of orthoclase to microcline should be indicated on the diagram by an area, means that within a restricted range of temperature and composition, *FGH*, both orthoclase and microcline can be in equilibrium. *H* is an "invariant" point, in the language of the phase rule. This means that any change in temperature or composition or both destroys one of the phases. At *H* there are three phases present: *H* as soda orthoclase[4], *H* as soda microcline,[5] and *I* as potash albite.[6] The phase

[1] Specimen 989.

[2] *Op. cit.*, pp. 348, 188. [3] *Op. cit.*, p. 256, Fig. 83. [4] $Or_{69}Ab_{31}$. [5] $Mi_{69}Ab_{31}$.

[6] $K\text{-feldspar}_{11}Ab_{89}$. The noncommittal "K-feldspar" is used because it is not definitely known whether it is microcline or orthoclase.

rule states that one of the phases must of necessity be destroyed[1] which, according to the diagram, is impossible. This absurdity can be appreciated by an illustration. Consider the solid substances *H* and *I* as already mentioned, composed of three phases, soda orthoclase, soda microcline, and potash albite. Let the temperature be lowered 5 degrees and the composition be enriched by 1 per cent of $KAlSi_3O_8$, shifting the point to a position within the triangle *FGH*. Within this area orthoclase and microcline are in equilibrium. Now one of the phases must disappear, according to the rule. Potash albite should then vanish. But how? Apparently the diagram is in error. Perhaps the error is not really in the diagram after all, but rather in our insistence that all three phases *are in equilibrium* with each other. The diagram would be correct if it was stated to be an "unstable equilibrium" diagram. A thoroughly satisfactory diagram showing the dimorphism of the potash component would have the inversion boundary indicated by a line, and not by an area.

The real point is that we should not fit the feldspars to the diagram, but rather the diagram to the feldspars. Thus if Mäkinen's diagram is for plutonic feldspars, indicating cooling slowly under quiet conditions, we can expect that orthoclase can form and remain unchanged during the cooling of the rock, until jarred or subjected to variable pressure. Then it would pass from the potential microcline form into the stable modification microcline, not all at once probably, but by slow degrees, and hence orthoclase and microcline would exist side by side during the time interval of change. A diagram to express this would obviously be an unstable equilibrium diagram. Mäkinen's diagram is incorrect if perfect equilibrium is insisted upon, but it is very likely relatively correct if unstable conditions are to be represented graphically.

The writer through thermal treatment[2] has been led to suspect that the transition range, in which both orthoclasic and microclinic feldspars exist, is to be represented by a transition line with the

[1] The mathematical expression of the phase rule is $C-P+2=F$, where C = number of components, P the number of phases and F number of degrees of freedom. $C=2$. ($KAlSi_3O_8$ and $NaAlSi_3O_8$.) $P=3$ (as said above). Hence $2-3+2=1$. But we said that *H* is invariant which should give us a zero for an answer. (All this provided equilibrium prevailed.) We can conclude therefore that the diagram is in error.

[2] Experiments were conducted in the laboratories of the department of physics of the University of Rochester in platinum furnaces. Temperature was measured by platinum-iridium pyrometers of high quality.

$KAlSi_3O_8$ end higher than the soda rich ranges. This can be expressed in other words: the temperature range of inversion is lowered by an increase of soda. This is contrary to Mäkinen's diagram. It is not the purpose here to emphasize this point unduly, but merely to suggest where additional light is desired.

Let us briefly examine the diagram of Marc.[1] Here the dimorphism of both components of the system is indicated. He says (in translation), "Whether the transition point *i* (Fig. 1 in Part II) is situated above the melting point *b* has not been determined." The temperature scale as originally given is only approximate and consequently the writer has taken the liberty of shifting it to more nearly match that of Mäkinen.

X-RAY ANALYSIS

Kozu, Endo, Suzuki, and Seto[2] have investigated specimens of adularia, moonstone, and sanidine with the X-ray spectroscope. Their discoveries are important. The adularia ($Or_{88.3}$ $Ab_{9.3}$ $An_{2.4}$) from St. Gottard was shown to have a single space-lattice which was unaltered by heating over the whole temperature range of its crystalline state. A Ceylon moonstone ($Or_{74.4}$ $Ab_{23.1}$ $An_{2.5}$), however, exhibited two space lattices[3] at all temperatures below 700° C. Above this temperature it became a single space-lattice system. A thin section of a moonstone from Ceylon[4] which may have been similar or identical with the material studied by Kozu et al., proved to be a cryptoperthite, microscopically agreeing well with the results of X-ray analysis. A moonstone from Korea ($Or_{61.9}$ $Ab_{32.7}$ $An_{5.4}$), a feldspar still richer in soda, exhibited the same property but the temperature of the passage from a two-space lattice structure to a single-space lattice system was about 500° C. In contrast to the latter, a sanidine from the Eifel ($Or_{76.9}$ $Ab_{21.8}$ $An_{1.3}$) behaved as though it was a homogeneous solid solution of orthoclase and "barbierite." "As is well known, however, the Eifel sanidine has a peculiar optic property, easily variable optic axial angle with the change in temperature, that is, an unstable molecular structure with respect to temperature. Though we cannot enter into the discussion of this

[1] Robert Marc, *Chemische Gleichgewichtslehre*, 1911, p. 102.

[2] *Science Reports of Tohoku University* (Sendai, Japan), Series III, Vol. I, No. 1.

[3] As shown by two sets of Laue photographs. A cryptoperthite.

[4] Purchased from Ward's Natural Science Establishment. Specimen No. 1394.

in detail at present, it is obvious that further researches would bring us very interesting and important results. . . . ."[1] It is evidently a metastable solid solution under molecular stress, tending to develop into a two-phase system, but prevented from doing so by the high viscosity which is characteristic of the solid state.

The investigation of these moonstones calls our attention to the feldspars called cryptoperthites. Such feldspars represent transitional stages from the unstable solid solution, anorthoclase, to stable perthite and which without much doubt can be classified as solid colloids—almost isocolloids. The passage from anorthoclase to perthite is through the intermediate stages of crypto-and microperthite; from a "molecular" dispersed system through a colloidal dispersed state to a mechanical intergrowth.

While X-ray analysis throws much-needed light upon internal arrangement of the atoms the question of the degree of equilibrium attained by each given specimen is still unsolved, for these minerals have different origins and, as already pointed out, furnish data for different diagrams. Here is a problem for the future, in the solution of which the Tohoku University investigators should have a prominent share.

In addition to their X-ray analyses these Japanese workers have conducted a series of thermal experiments that agree in large measure with the results obtained by Vogt, Dittler, Johannsson, Vegard, Watts, Douglas, Mäkinen, and the writer.[2]

[1] S. Kozu and K. Seto, "Sanidine from the Eifel," *Science Repts., Tohoku Univ.* (Sendai, Japan), Ser. III, Vol. I, No. 1, p. 27.

[2] J. H. L. Vogt, "Physikalish-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tsch. Min. Petro. Mitt.*, XXIV (1905), XXV (1906), and XXVII (1908); E. Dittler, "Die Schmelzpunktskurve von Kalinatronfeldspaten," *ibid.*, XXXI (1912), 513; "Über die Darstellung kalihaltiger basischer Plagioklase," *Min. und Petro.* Neue Folge., XXIX (1910), 273–333; "Über das Verhalten des Orthoklase zu Andesin und Celsian über seine Stabilität in künstlichen Schmelzen," *Tsch. Min. Petro. Mitt.*, XXX (1911), 118–27; H. E. Johansson, "Om fältspaternas sammansättning och bildings forhållanden," *Diese Zeitschr.*, XXVII (1905), 338; Vegard, "Die Konstitution der Mischkrystalle," *Phys. Zeitschr.*, XVIII (No. 15, 1917), 93–96; A. C. Watts, "The Feldspars of the New England and North Appalachian States," *U.S. Bur. Mines Bull. 92*, 1916; J. A. Douglas, "On Changes of Physical Constants in Minerals [by heating]," *Quar. Jour. Geol. Soc.*, LXIII (1907), 159; Eero Mäkinen, "Über die Alkalifeldspäte," *Geol. Foren. Förhandl.*, XXXIX (1917), H. 2. For synthesis see F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv. Bull. 606*, 364–67.

In the course of thermal studies of his own the writer has found that a convenient test for the development of glass (or leucite) on the margins of crushed fragments which have been subjected to high temperature is to measure the indices of refraction by the immersion method,[1] using the Becké test, with monochromatic light. This will reveal the thinnest possible shell of glass upon an unaltered core.

Such thermal experiments would suggest that the liquidus and solidus curves of some of the diagrams should not be so flat as those of Mäkinen, etc. Mäkinen has shown that a perthite ($Mi_{68}Ab_{30}An_2$) when heated to 1200° C.[2] exhibited incipient fusion and says (in translation): "The perthite albite is almost entirely melted and contained abundant blebs [bubbles]. The microcline [phase] was so much altered that the extinction angle on the (001) face in the proximity of the melted albite amounts to 9-10° and as for the rest it amounts to 15° as the maximum." Here Mäkinen had the chance of drawing a valuable conclusion. Consultation of the optical constants of the feldspars would have at once suggested that anorthoclase had been developed by re-solution. The writer has satisfied himself through actual thermal experiments that the long heating of the microcline-microperthite (hypoperthite) from Verona, Ontario, Canada (approximately $Mi_{41}Ab_{58}Ab_1$),[3] at 1000° C. produced anorthoclase of approximately the same composition as the sum of the two phases of the original.

[*To be continued*]

A PRELIMINARY REPORT ON THE MICROSCOPY OF ANTHRACITE COAL

HOMER G. TURNER AND H. R. RANDALL
Lehigh University

INTRODUCTION

In connection with petrographic studies during the winter of 1921–22, the authors became interested in the microscopic characteristics of anthracite coal. A review of the literature, however, revealed the fact that very little had been accomplished in this field. The reason appeared to be the inability to prepare specimens that would show their microscopic structures. An investigation was therefore begun which had as its purpose the treatment of anthracite so that its microscopic features could be easily discerned. The results of the method finally adopted are revealed in the accompanying photographs which show some of the most conspicuous structures observed. While no attempt is made at this time to classify definitely the organic forms, some tentative conclusions nevertheless seem warranted from the observations thus far made.

The coal used in connection with this investigation came from the Northern, Western Middle, and Southern Fields of the Pennsylvania anthracite region. Specimens from the Buck Mountain, Primrose, and Mammoth beds from each field were studied.

METHODS ADOPTED

After considerable experimentation with thin sections and various chemical reagents, with unsatisfactory results, the method herein described was developed. It consists briefly of obtaining a polished surface on the coal and etching with heat. Although pieces of various sizes and shapes are used, blocks of coal about two centimeters square take the most uniform polish and are large enough to be handled with ease. Larger pieces can be used provided that one has the equipment for polishing them, and such may be

desirable when one wishes to study some particular form which extends for some distance through the coal. The microscopic examination of a large surface, however, is very fatiguing. Furthermore, one may easily miss important forms or spend hours re-locating minute structures.

Small blocks are therefore cut from the coal by means of an ordinary hacksaw. Two surfaces, one parallel to the bedding and one at right angles to it, are ground to planes. All sharp edges are beveled slightly to prevent pieces from breaking off and scratching during the subsequent smoothing. These plane surfaces are then polished to remove saw marks and scratches.

Different ways of obtaining a polish were tried. The method which gave the quickest and most satisfactory results, however, consisted of first grinding on a revolving iron lap with medium-sized carborundum powder and water; next smoothing by hand on plate glass, using one-minute tripoli powder and water; and finally polishing by rubbing in one direction on a novaculite honestone with a paste of rouge and water. This paste should be fairly thick, for the best polish is obtained when the specimen is rubbed until the paste is almost dry and the coal sticks to the hone. A few brisk rubs on dry chamois with rouge, or on broadcloth with diamantine, remove all water stains and leave a very high gloss. Chromic oxide may be substituted for rouge with equally good results. On account of its green color it possesses the added advantage of not being confused with the reddish oxide of iron resulting from the oxidation of iron compounds in the etched coal.

The polished surface obtained in the above way, although not entirely free from scratches, suffices for good results. When the few remaining scratches interfere, they are removed by rubbing on a dry hone without rouge and finally polishing further with diamantine on a flat block covered with broadcloth. The hone, when used dry, has a tendency to become covered with a dark gumlike substance due to the adherence of fine particles of coal. This is overcome by rubbing down from time to time with a second hone, using a lather of soap and water. Not only is the gumlike coating removed but the surface of the hone is also kept flat by this treatment.

The polished specimen is finally placed in a drying oven over a Bunsen burner and heated from room temperature to about 220 degrees Centigrade, to remove moisture, and to obviate splitting of the surface due to sudden heating during the etching process. After this temperature has been maintained for about an hour, the specimen is removed with the forceps and the polished surface immediately brought to a red heat by means of the oxidizing blow-pipe flame. A differential oxidation is thus produced which reveals the structure in relief without destroying the polish to any great extent. The surface should appear only slightly foggy owing to an almost imperceptible film of ash.

The duller layers in the coal etch more rapidly than the bright ones, making it necessary at times to warm and etch repeatedly in order to bring out the greatest detail. Those varieties which show little lamination and are made up almost wholly of jetty bright coal must be etched in a little different way to overcome splitting of the surface. Instead of the oven a sand bath is used. The coal is immersed in clean dry sand with only the polished surface exposed. The bath is placed over a battery of four Bunsen burners and brought to a temperature of 300 degrees Centigrade. This temperature is maintained for about half an hour when the polished surface is heated in place to a bright red heat with a blast lamp, using a rather large blue flame which is played slowly back and forth over the surface. A little experience will demonstrate the advisability of re-etching to further define partially hidden structure.

Various attempts were also made to utilize oxygen in etching. A stream of cold oxygen was directed on the surface of a specimen heated to about 400° Centigrade, but only served to keep the surface cool and prevent etching. Warm oxygen used in the same way gave no better results. Oxygen at very high temperatures was not used in this way. Etching is produced, however, by heating polished specimens in an atmosphere of hot oxygen under slight pressure. In the latter case the coal is placed in a piece of glass combustion tubing about two feet long. Oxygen is passed through water in a wash bottle and into the combustion tube through a rubber stopper

in the upper end. In the lower end is placed a two-hole rubber stopper through which a thermometer is inserted. The temperature is raised to 250° Centigrade by heating the tube with a Bunsen burner just beyond the coal, between it and the intake. The action is continued until the polish begins to grow dim. Great care must be exercised to prevent the surface of the coal from coking. The forms revealed by this method of treatment are not as sharply defined as those produced by direct heating and since it requires more time, care, and apparatus, it is not recommended where direct heating can be used. The only advantage is that the surface remains flat and therefore shows some structures in coal which might otherwise be largely reduced to fragments by direct heating.

The etched coal is finally studied with the metallographic microscope, using vertical illumination from a carbon arc. A good working objective is one of medium power giving a magnification of about 250 diameters. A clean-cut image can be obtained up to a magnification of 1,000 diameters. In all cases the eye can discern finer details than are shown in the photographs.

The method as outlined, except for a modification of the etching process, has been successfully applied to bituminous coal and cannel coal. The polished cannel coal was held for a few moments in the oxidizing Bunsen flame without being previously heated in the oven. Good results can probably be obtained with carbonaceous shale and other materials of similar nature.

GENERAL RESULTS

A preliminary examination of the specimens of anthracite from the different fields shows that all varieties are composed of laminae of different luster, texture, and thickness. Brilliant jet black layers alternate with glossy black or gray bands in which are imbedded thin sheets of dull material resembling charcoal. The brilliant black layers vary in thickness from a few microns to many centimeters. The glossy gray bands are thicker than the jet black ones although, on close inspection, they are shown to contain many thin sheets of the brilliant black coal and thin sheets of dull material. The brilliant layers are more compact than the duller ones and

FIG. 1.—(×170) crosswise to the bedding, from Pennsylvania anthracite. Shows spore exines. The markings on the spores are probably lines of dehiscence. This group of spore exines was found in the duller layers.

FIG. 2.—Section (×170) crosswise to the bedding, from Pennsylvania anthracite. Shows large, wrinkled spore exines found in the duller layers.

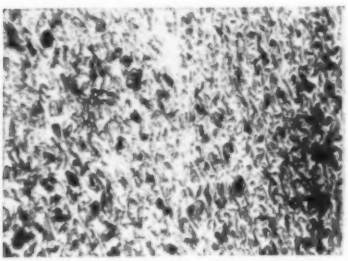

FIG. 3.—Section (×125) crosswise to the bedding, from Pennsylvania anthracite, showing crushed and warped cells, observed in a zone surrounding a knot of almost structureless charcoal.

possess a more perfect conchoidal fracture. Where they are thick, the broken surface often shows rounded or oval fracture forms. Although the above distinctions hold true for most of the anthracite, some varieties appear at first glance to be composed wholly of the brilliant coal, revealing their various laminae only on careful examination.

Mineral charcoal was quite abundant in almost all the coal examined. Cleaving coal parallel to the bedding exposed charcoal-covered surfaces in every specimen which showed distinct lamination. On the other hand the varieties which were poorly laminated and almost uniform in luster contained very little charcoal.

In addition to the thin sheets of charcoal so commonly found in the bedding planes, one finds occasional large fragments which cross several of the horizontal layers. These large pieces of charcoal are of particular interest because of the fact that they show in most cases perfect cells almost entirely devoid of filling. The cell walls are thicker than those of the original wood and appear to be lined with a bright jet black layer which permits good photographs by reflected light. All

the large lumps of charcoal examined have the structure of conifer wood. Rings of growth, medullary rays, and bordered pits are distinctly shown.

Ordinary commercial charcoal differs from the mineral charcoal in no essential detail when examined with the microscope. This condition seems to argue against regarding the charcoal as the product of forest fires, for it seems probable that the cells would either have been filled with the putrefaction product solutions during subsequent immersion in the bog, or crushed under the pressure of overlying material.

The brilliant layers of the coals examined show, under the microscope, either no structure or a preponderance of wood fiber and wood cells. In the glossy duller layers are found spore exines, former resinous materials, apparent vascular bundles, cuticles, wood fiber, cell laminae, and other forms not yet identified. The thin dull black layers usually show wood fiber and wood cells either well preserved or crushed to an almost structureless mass. Further microscopic details can be most advantageously described in the legends of the microphotography.

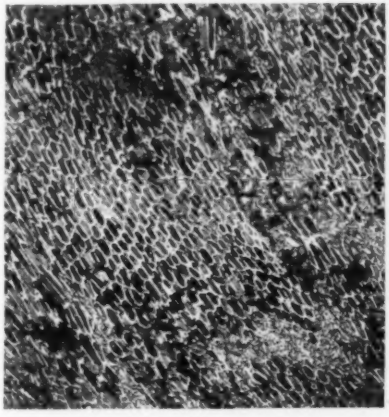

FIG. 4.—Section (×50) parallel to the bedding of the Forge split of the Mammoth bed from Nanticoke, Pennsylvania. A section of wood showing original cell laminae. The remarkable preservation of these cells may be due in part to the silicious filling shown by the gray areas within the cell walls, although some of the cells are filled with black, lusterless carbonaceous material.

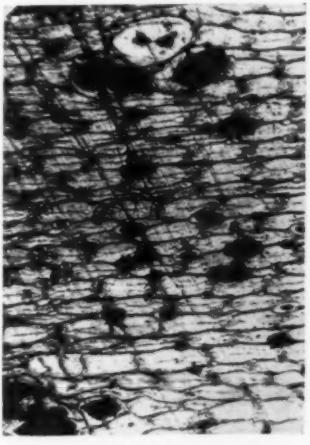

FIG. 5.—Section (×126) crosswise to the bedding and oblique to an apparent stem in anthracite from Pennsylvania. This section is of particular interest because it is in the brilliant jetty coal and not in the duller layers where such forms are usually found.

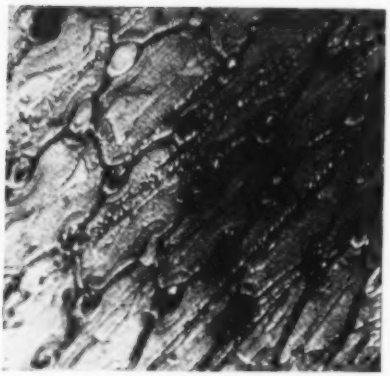

FIG. 6.—A part of Fig. 5 (×500) showing the great detail revealed by the method of treatment described in this paper. Note the delicate dumbbell-shaped membrane with the cells and the elliptical markings surrounding the small knots along the cells walls.

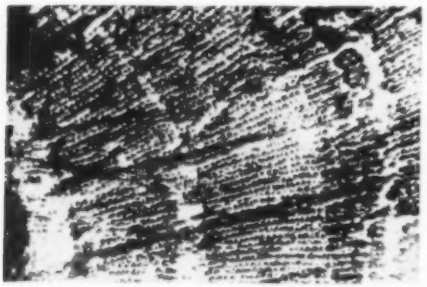

FIG. 7.—Cross section (×83) of a charcoal stem of coniferous wood found in anthracite from coal measures around Minersville, Pennsylvania. Note the well-defined medullary rays and annual rings. The rather thick cell walls are composed almost entirely of bright, jetty material making possible this photograph by reflected light. The black spots within the cell walls are holes.

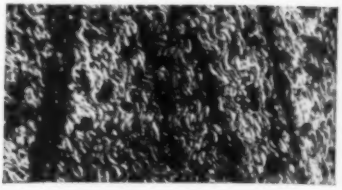

FIG. 8.—Section (×118) crosswise to the bedding of coal from the Primrose bed, William Penn colliery. This section through the duller layers shows wood fiber much contorted.

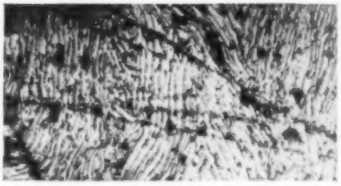

FIG. 9.—Section (×118) crosswise to the bedding of the Primrose bed showing less flattened wood fiber.

FIG. 10.—Section (×124) crosswise to the bedding, from Pennsylvania Anthracite. This section through the duller layers shows a somewhat macerated wood fragment containing round bodies which are probably vessels formerly filled with resin or gum.

Almost all the specimens studied show remarkably smooth and regular vertical joints at right angles to the bedding planes. Some of the less distinctly laminated varieties possess, in addition to the regular vertical joints, bright slickensided surfaces at low angles to the bedding. Those varieties which show distinct lamination can be cleaved easily parallel to the bedding while the more massive types possess almost no cleavage.

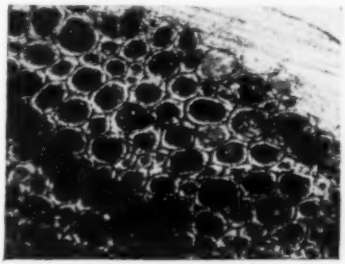

FIG. 11.—Section (×125) crosswise to the bedding of coal representing the Forge split of the Mammoth from Nanticoke, Pennsylvania. Shows cells of xylem or phloem of a vascular bundle. This is a section through a dull knot. Some of the cells are partly filled with small grains of pyrite which do not show in the photograph. The black centers are dull carbonaceous material.

Aside from the more splendent luster, anthracite is shown, from the above description, to possess all the essential megascopic characteristics of bituminous coal; in addition it shows the same types of organisms under the microscope; and further, these organisms are apparently no more distorted than those of the bituminous coal.

The authors expect to make a detailed study of some of the best-known anthracite seams of Pennsylvania. It is hoped that this study will lead to a better knowledge of the factors involved in the origin of anthracite. From the observations thus far made, it seems highly probable, also, that the various beds can be correlated through the identification of dominant plant types and through other microscopic characteristics, although this will obviously involve a great deal of study and observation both in the laboratory and in the field.

The writers wish to thank Mr. John H. Stoll and Mr. R. H. Christ, of the Bethlehem Steel Company, the officials of the Susquehanna Collieries Company, Professor H. B. Pulsifer, of the metallurgy department of Lehigh University, Doctor B. L. Miller, of the geology department of Lehigh University, David White, of the United States Geological Survey, for their kindly co-operation.

GEOLOGY OF THE PHILIPSBURG REGION OF QUEBEC WITH NOTES ON CORRELATIONS WITHIN THE BEEKMANTOWN

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    Scarcity of fossils
    Strike Faults and Minor Folds
  Division B
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Similarity of Philipsburg and East Shoreham Sections
Lower Beekmantown
Middle Beekmantown
Upper Beekmantown
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Conclusions

INTRODUCTION

The region along the northeastern shore of Lake Champlain, which in this paper will be termed "the Philipsburg region" because the area especially under consideration extends northeast and southwest from the town of Philipsburg, Quebec, has been studied by many geologists, Canadian and American. The rocks of this vicinity occupy a stratigraphic position in that zone of uncertainty on the Cambro-Ordovician boundary, which at the present time is an important question of controversy. For this reason they have been studied by the writer with the utmost care, with the hope that more facts might be gained concerning the events which transpired between the deposition of the Potsdam and the Chazy beds in the Champlain Valley.

Although the rocks of the Philipsburg region may be said to be well known, they are at present far from being well understood.

The complexity induced by a complicated system of close folding and overthrust faulting has paved the way for varying interpretations of structure, while a dearth of fossils has resulted in erroneous correlations based mainly on lithological similarities and an insufficient study of what few fossil remains have been obtained. The writer spent eleven weeks in this area during the summer of 1922. This time was largely devoted to a thorough search of all available and likely outcrops for fossils. The great bulk of the rock was barren, but determinable fossils were found at seven different horizons; at one in great abundance. Several new forms were discovered and will be described at a later date. It has been thought advisable to present in some detail the structural and lithological peculiarities of the strata in this region, because in some cases the correlations suggested in this paper must rest largely on inorganic evidence. Since the proof or disproof of a widespread Ozarkian system must rest on the complete understanding of such sections as that of the Philipsburg region, such a detailed presentation seems justified. The purpose of this paper is to present a summary of the evidence, from field and faunal studies, that no Ozarkian rocks are present in this area; that no great diastrophic or faunal breaks, which are the accepted basis for the separation of geological systems, occur in the northeastern part of the Champlain Valley. If the correlations suggested here survive the test of detailed study in other regions to the west and southwest of Lake Champlain, it must follow that not only at Philipsburg, but throughout the Champlain Valley, deposition was not interrupted by any great break until the end of Beekmantown times.

STRUCTURAL RELATIONSHIPS IN THE PHILIPSBURG SERIES

The rocks of the Philipsburg series occupy a position in northern Vermont and southern Quebec between the east shore of Missisquoi Bay and the valley of the Rock River, two miles to the east (Fig. 1). Their southern extremity can be seen in an outcrop along the line of the Vermont Central Railroad about 500 yards northeast of the mouth of Rock River, Vermont. The strike here is N. 28° E. Following this direction southwestwardly across the lowland of the Rock River, we next find rocks of a different char-

acter which contain Black River fossils in abundance. Similarly following in the direction of the dip, which is S. 21° E., we find the section terminated one mile to the east by a ridge of quartzitic rock

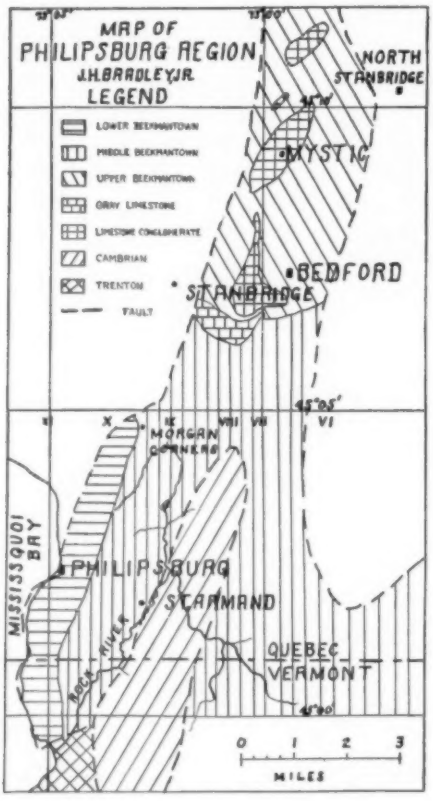

FIG. 1

from which Upper Cambrian fossils have long been known. The faulting which terminated the Beekmantown section to south and east will be discussed later.

Following northward along the strike from the southern extension of the series, we can trace the lower bed two miles across the

international boundary into Quebec to Philipsburg two miles beyond. From Philipsburg the strike, which maintains a northeasterly direction, carries us away from the lake. In this direction the series can be traced through Morgan's Corners (formerly Blood's Corners) to the village of Bedford, where higher strata come in, and beyond to Mystic. The northernmost outcrop of the highest bed which is traceable, occurs about two miles north of Mystic on the twenty-second lot of range six, Stanbridge, Quebec.

Using this outcrop as an arbitrary northern limit of the series, the area under discussion is roughly fifteen miles long. The width varies from about a mile and a half on the south and north to about three and a half miles in the middle. On the east, west, and south the section is truncated by faults. To the north the prevailing limestone gives way to slates whose structure and stratigraphy are as yet very little understood.

In 1863 the intricacies of the geology of the Philipsburg region were made known by Logan in his admirable report on the geology of Canada.[1] This work was done in great detail and with great accuracy. The general division of the section into four parts on the basis of lithology seems a good one for the sake of discussion, and in this paper the writer will adhere to Logan's Divisions A, B, C, and D. It must be remembered, however, that these divisions, although marked lithologic units, are not necessarily stratigraphic or structural units. This fact will be made clearer in the subsequent discussion. Logan's section, in descending order, is briefly as follows:

	Feet
D	
3. Grey and black striped slates interstratified with thin beds of black limestone and limestone conglomerate	1,500
2. Black and greenish argillaceous slates with patches of limestone conglomerate and bands of magnesian slates	1,000
1. Black limestone conglomerates, composed chiefly of the ruins of thick bedded limestones of division C	300
	2,800
C	
2. Black slates and thin-bedded black limestones, toward the top imperfectly seen	170
1. Black and dark grey compact pure massive limestones with a few bands of dove grey	150
	320

[1] Sir William Logan, *Geology of Canada*, 1863, pp. 175–280; 844–54.

B

	Feet
5. Black limestones, some of them massive, weathering bluish-grey; interstratified toward the bottom with black and dark grey yellow weathering magnesian beds	350
4. Black slaty thin-bedded nodular limestones with beds of purer limestone toward the base	300
3. Dark bluish-grey thin-bedded nodular limestone with some magnesian slate	150
2. Dark grey and black limestone, some of the beds magnesian	120
1. White and dove grey pure limestones, with some yellow-weathering magnesian bands	120
	1,040

A

3. Reddish-grey brown weathering dolomites, and black dolomites with some thin-bedded black limestones	200
2. White and dove grey pure compact limestones	100
1. Dark grey and yellowish-white dolomites, weathering grey and yellowish-brown	400
	700

Total thickness.....4,800 feet

DIVISION A

The lowest members of the series are well exposed at the town of Philipsburg and follow the shore of Lake Champlain south to the Vermont-Quebec boundary. At this place the rocks rise in cliffs which form an almost perpendicular wall at the water's edge, and are known locally as the "High Rocks." These cliffs continue southward with diminishing height almost to Rock Bay, two miles south of the boundary. Although these beds can be followed northeastward from Philipsburg for about eight miles, it is the "High Rocks" exposure which sheds most light upon their structural arrangement. At this point overthrust and reverse faulting, and close folding are common phenomena. The evidence of this exposure is that the thrusting force acted normal to the strike with the overthrust from the southeast. The close folding so clearly displayed here is typical of folding throughout the entire Philipsburg area. The pressure came probably after the beds had been lithified, picking up the thinner beds into folds and overthrusting or reverse faulting the thicker beds. Two minor overthrust faults can be seen in this lake shore exposure and two minor reverse faults

as well as several partly overturned synclines and anticlines—all in limestone of the lower part of the grayer facies of Logan's A1.

It might be well to mention at once that one important characteristic of the entire series is that the average outcrop gives little or no evidence of any folding whatsoever, so that it is particularly difficult and often impossible to tell when the same stratum has been repeated in a close fold. Most of the beds—if they may be called beds—are thick, and the trend of the rocks, although it can usually be ascertained in general, is not easily measured with exactness because the bedding is so obscure in many places. For this reason and for reasons to appear later in connection with a discussion of minor folding, an accurate measurement of thickness is well-nigh impossible.

The lowest beds of A1 rest upon crumpled beds of black slates interstratified with thin bedded, brownish weathering calcareous strata. These slates occupy a narrow strip of lake shore from Philipsburg south. They show marked signs of deformation, but in no outcrop do they appear to have suffered folding contemporaneously with the overlying limestones. Although no fossils appear to substantiate the general belief that the slates are of Trenton age, neither is there paleontological proof that they belong to the older age of the overlying rocks. The structural evidence, on the other hand, though scanty, would argue for Logan's interpretation, that the limestones were thrust over the slates. The folding and faulting just mentioned in the overlying A1 beds can be explained best by a thrusting force from the southeast. The same force if strong enough, could have acted on the entire mass of limestone as a competent block, thrusting it to west and north.

Although in the large, the lake shore exposure of the strata comprising A1 bears out the general evidence of neighboring regions regarding the direction of the thrusting force, there is clear evidence locally of overthrusts from the northwest. These thrusts directly opposed to the direction of the main thrusting force can be explained on the basis of initial dip or a vertical shifting of the horizon of major thrust.[1]

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., Ann. Rept. 13*, Part 2 (1892).

On the shore of Missisquoi Bay, three-fourths of a mile north of the international boundary, a group of thin-bedded siliceous strata underlie the massive, apparently unbedded limestone of A1. The dip is gently to the east and the beds are conglomeratic in part, with well-rounded pebbles as large as eight inches across. These strata are associated in places with very thin-bedded black shale. The entire thickness is less than ten feet and at the top the strata grade into the calcareous rock. These beds are interesting in view of Walcott's statement[1] that "a small outcrop of Potsdam sandstone, with characteristic fossils, subjacent to the limestone of the Calciferous" occurs on the lake shore near Philipsburg.

These siliceous beds are the only strata similar to the outcrop described by Walcott that a week's search revealed to the writer. Following north along the shore, in one place three-quarters of a mile south of Philipsburg, a marked unconformity was found between the massive overlying limestones of A1 and the narrow layers of sandstone which overlie the Champlain fault. Here the sandstone dips to the east as it does farther south. The overlying limestones, in this place apparently thin-bedded, meet the underlying sandstones almost at right angle, and then after bending into a small anticline, resume their easterly dip parallel to that of the sandstone. It is the opinion of the writer that this local difference in the attitude of the strata is due purely to differential folding in the two beds rather than to causes implying uplift and erosion.

A1 proper is composed of two lithologically different limestones, which maintain their distinctive qualities in most of the places where the members can be observed. The folded rocks mentioned above are of granular nature, largely limestone, but chemically impure with magnesium and mechanically impure with detrital quartz. A few brown weathering, highly magnesian beds are noticeable. These strata are the lowest of the series and predominantly grey in color, weathering grey and brown; they will be spoken of here as the grey facies of A1.

The beds of the grey facies are somewhat thinner than the apparently overlying yellowish grey and buff (weathering yellow brown) granular limestone. These beds will be referred to as the buff facies

[1] Charles D. Walcott, *Bull. Geol. Soc. Am.*, Vol. I, p. 512.

of A1. It is likely that as a general rule the compressive forces effected folding in the grey facies, and fracture in the buff facies. The most southerly extension of the "high rocks" exposure on the shore south of the boundary exposes well the buff facies of A1. There is a slight valley between these cliffs and those of the grey facies to the north. Although the bedding in the buff facies in most places is almost impossible to determine, the impression given is that they stand almost vertically. If this is the case and if the buff facies really overlies the grey, the buff beds have been faulted down and upturned in the general deformation which closely folded the underlying grey strata.

About 250 yards east from the lake at the international boundary the yellowish white, brown weathering magnesian limestones of the buff facies come in on top of the grey. In one place one-eighth mile south of the boundary, this line of contact was traced in a continuous outcrop for 100 yards. At the southern extremity of this outcrop the yellow white limestone appeared to be standing on end, in very much the same attitude that it appears to be standing in the escarpment three-fourths of a mile south of the boundary on the lake shore. In this place it would seem that the yellow white limestone is above and younger than the grey limestone. Following the boundary east to the valley parallel to the lake which is occupied by the Philipsburg–Highgate Springs road, the limestone of the grey and buff facies seems to become interbedded and finally grades into a pure compact dove grey limestone. The outcrops of these beds are conspicuous because they weather smooth and very often light grey to white. These beds belong to Logan's A2. Beds of A1 and A2 can be followed from the Boundary northeast by almost uninterrupted exposures to Morgan's Corners. Here a well defined line of fault is beautifully shown north of the road running east to Bedford.

A3 follows A2 first with reddish grey granular beds of limestone and these in turn by black limestone. In an unpublished letter, Dr. G. A. Young, of the Geological Survey of Canada, has recognized these two quite distinct phases of Logan's A3. He named these members A3*a* and A3*b*. Since the integrity of these divisions is maintained in the faulted zone at Morgan's Corners, it is important

to distinguish which part of A_3 is being dealt with. The lithology of the two members is well described by Logan.

Following the black beds of A_3b northeastward, the strike is seen to curve slowly to the east. At Morgan's Corners they are disrupted and turned up on end. Back of the schoolhouse at this place, beds of A_3b are seen to strike due east-west and to dip northward gently. Following this strike eastward, the beds shortly assume the vertical position. A little east of the schoolhouse the black A_3b beds have in contact with them to the south, the light grey to white, crystalline to granular, beds of lower members. The inference would be that the pressure which bent the rocks to the east along their strike across range 10 of St. Armand, finally caused the beds to break at this point. The rocks to the north of the fault were upthrown and turned vertically.

Following east, the black beds of A_3b fold over an anticlinal axis associated with beds of A_2. This fact leads to the conclusion that the faulting at Morgan's Corners was a result of pressure which died out in the direction of the anticline. If this is true, the dislocation in A_3 and A_2 at Morgan's Corners cannot be of great extent.

Scarcity of fossils in Division A.—It is unfortunate that in A_1, 2, and 3, with an assigned thickness of 700 feet, organic remains should be so rare. A careful search failed to discover in this entire thickness any remains of undoubted organic origin. Some few gastropods in a poor state of preservation and determinable only on the broadest generic lines, were found by former investigators. The scarcity of fossils has made the correlation of these lower beds exceedingly difficult. It is clearly evident from field observation that the A and B series are unbroken structurally. We have no evidence of uplift and erosion between A and B. Likewise, there is no evidence that A and B are separated by a fault. As a matter of fact, the separation of these beds into A and B on a structural basis, is wholly arbitrary, and a more logical arrangement would be to include A and B in the same series. On the other hand, some of the strata in B are highly fossiliferous. These fossiliferous beds of St. Armand and Stanbridge are the only reliable means of obtaining any light on the age of the rocks in Division A, so that in the absence of any break in deposition between A and B, the writer

has correlated A partly on the basis of its own lithological makeup, but largely on the faunal evidence of the overlying B strata.

It is possible that even if organisms were living in the waters which gave rise to the A beds, clastic deposition was so slow that the calcareous shells were dissolved and reprecipitated as normal lime rock before they could be buried and preserved as fossils. It is a striking fact that the few fossils found in A were but faint shadows of the original organisms. The state of preservation of these fossils strongly suggests that dissolution was active before the rocks were lithified, and only those individuals whose shells were thick and resistent, succeeded in being preserved.

Strike faults and Minor folds.—At the international boundary the beds of A can be followed down the dip with almost no concealment. To the casual observer, the beds would seem to be dipping to the southeast at a gentle and fairly constant angle. The rock is peculiarly massive and unbedded, and it is only with careful study that the true dip can be ascertained. In the section cited, between the lake shore and the road, the A1 beds are turned up practically on edge, possibly overturned in places. The pure, dove-grey beds of A2 show no good criteria for correct measurement of dip, except that they conform generally to the normal southeast dip of the whole series. A3, on the other hand, being made up of less pure, reddish-grey granular limestone, with magnesian beds, and shaly black limestones, shows the effect of compressive forces. At the international boundary the A3 beds, near their contact with those of A2, fold under a synclinal axis. One bed of A3*a* is prominently exposed where the strike can be followed without break around the nose of the trough. Other beds of A3*a*, which would not bend, are seen in a much faulted condition nearby, lying at various angles. This undulation in A3 appears to have been effected by a thrust from the southeast, causing a steeper dip on the east limb of the syncline and a gentler dip on the west limb.[1]

The folding in A1 on the lake shore was probably localized in horizons of the more thinly bedded strata of the grey facies. With the exception of these folds, seen and traceable on the surface, the mass of A as a whole is distorted more by faulting than folding.

[1] Sir William Logan, *op. cit.*, 1863, pp. 846, 847. See also Fig. 2.

Although it cannot be definitely proved by field evidence, it is probable that the province line section just described is crossed by transverse dislocations, which are suggested by the terraced nature of the outcrops. The occasional upturned dip of the lower strata of A can be explained in this way.

DIVISION B

By far the most important rocks of the Philipsburg region are those of the B series, because it is in them that structural features can be best traced, and from them the most fossils evidence was obtained. These rocks follow the beds of A and are well exposed in a syncline just west of St. Armand Station (Fig. 2). From here they strike across the township of St. Armand into Stanbridge, where they are succeeded conformably, about one mile south of

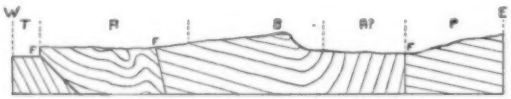

FIG. 2.—Diagrammatic section along the International Boundary, eastward from Mississquoi Bay. P, Potsdam; A, Lower Beekmantown; B, Middle Beekmantown; T, Trenton; F, fault. Horizontal scale, ½ inch = 1 mile; vertical scale exaggerated.

Bedford, by the strata of the C series. The higher beds can be traced from the vicinity of St. Armand village continuously to the region where they are succeeded by the beds of C. These strata are well described by Logan.

DIVISION C

Fossils were collected near the axis of the syncline from the massive black limestone of B5 about one mile north of St. Armand station on the Stanbridge road. The dip in the rocks at the roadside is 2°–4° S.W. About 300 yards west, an outcrop shows a dip of 10° S.E., thus marking the synclinal structure. From the outcrop on the road, several fragments of thick-shelled trilobites, and brachiopods were found. In a somewhat lower bed on the western flank of the syncline, surface indications of Maclurea ponderosa and

other large gastropods were common. The writer followed the B5 beds north to lots 6 and 7 of range 7, where the massive beds of C come in. In C1, practically the same fauna of thick-shelled forms was collected. This faunal similarity between B5 and C1 is important because it corroborates the structural evidence that C directly overlies B. There is no evidence of uplift and erosion.

The massive beds of C, although limited in their exposure, are striking because of their light-colored weathered surfaces and the peculiar smoothly rounded outcrops. They have been quarried for lime extensively in the past and are known as the "panther" rocks locally. The large coiled gastropods conspicuously outlined on their surfaces probably are the cause of this section's having been assigned to the Chazy, because of a remote similarity between Maclurea ponderosa and M. magna.

The existence of Logan's C2 between these conspicuous beds of C1 and the conglomerate of D has been doubted by some because of the nearness of outcrops of C1 to D1 on the sixth and seventh lots of the seventh and eighth ranges of Stanbridge. Although D1 is very poorly exposed, the present writer found indications of black slates in several places underlying the first conglomerate band of D. On lot seven, range seven, a small outcrop of slate was found within stone's throw of C1 on the south and D1 to the north. It is probable, however, that Logan's thickness of 170 feet is too great. C2 is probably nearer to 50 feet in thickness. The dips of C1 in this region show the same syniclinal arrangement noticed at St. Armand station. The slope of the trough becomes more gentle to the northeast.

DIVISION D

The massive black limestone conglomerates of D1 outcrop along the line of the Canadian Pacific Railway on range eight Stanbridge between Stanbridge station and Bedford. The strike here is N.65 E. Conglomeratic bands can be followed from this point northeastward to lot 22 range six Stanbridge. Towards the bottom, D1 appears to be in places a massive non-conglomeratic limestone. Three-quarters of a mile on the wagon road east of Stanbridge station,

well-rounded pebbles of sandstone occur with the black limestone pebbles. This indicates that in this place at least we have a normal conglomerate.

Following the elliptical outcrops of D1 to the road about one mile north of Mystic, which runs from Notre Dame to North Stanbridge, the conglomerate can be seen in outcrops which might be called typical. True bedding is absent. The rock is composed largely of elongate fragments of dark grey and black limestone weathering grey. The matrix, likewise of black granular limestone, weathers dark brown and black, thus showing the shape of the pebbles to good advantage. In some places the pebbles are scarcer and the rock has the aspect of a massive black limestone. In other places the rock is made up almost entirely of fragments. The pebbles range from small round masses one-half inch across to pieces one to two feet in diameter. Associated with these rounder fragments are the more common elongate pieces which range from one-half inch to two feet in length and from one-half to one and a half inches in width. These long fragments have a general alignment normal to the strike and clearly show that they are the broken, reworked slabs of a former thin-bedded black limestone whose fragments have not been transported very far.

Southwest along the strike, the conglomerate was found to contain, in places, a few irregular masses of black slate. In places a nodular condition was seen, as if mud had been deposited with the lime. At Mystic Station good outcrops of conglomerate show bedding. Some of the strata, particularly those with an abundance of vein calcite, were only slightly conglomeratic, and were chiefly composed of massive black limestone. A little farther south fossils were found in the matrix.

To obtain a complete picture of this conglomerate we must study the outcrops on lot two and twenty-two, range six. In one place the fragments have a peculiarly brecciated appearance. Pieces of dove grey pure limestone compose the greater part of the beds. The paste is of darker material, in places slaty and largely calcareous. In one place above the more brecciated zone, a bed of massive, partly broken grey limestone occurs. No paste seems to be mixed in with this limestone; the broken fragments appear to have been

recemented by lime dissolved from themselves. From this rock a good collection of fossils was obtained.

Half a mile south of Bedford a much sheared black limestone dipping to the northwest is overlain by a band of conglomerate apparently dipping to the southeast. Much shearing and crumpling occurs at the contact. A thrust fault of minor magnitude probably occurred here. This band of conglomerate is probably of a different horizon from the one described above and belongs to Logan's D_3. Many large angular and sub-angular fragments occur and the material is entirely unassorted as to size.

Logan's conclusion that the lower strata of D were formed from the breaking down of the massive beds of C_1 is not substantiated by fossil evidence. Nowhere in D has the thick-shelled gastropod fauna of C_1 been found. In fact, gastropods are conspicuously absent from the fauna from D. Likewise the lithology of the conglomerates indicates that originally the strata of D were predominantly very weak and thin bedded. There is no evidence of any thin bedding in C_1.

Although the section from D_1 upward is in need of revision, particularly the great thickness of slate which occupy the spaces between the ridges of more resistent limestone conglomerate, a few facts are clearly present which throw light on the genesis of D. The intercalation of thin dolomitic beds with much of the slate, the great abundance of slate, as well as the presence of shallow water organisms in the paste of the conglomerate indicate a shallow-water origin. The general absence of rounding in the fragments of the conglomerate and their general allignment gainsay transportation and point to deformation of the unconsolidated beds in situ. This deformation was probably due to the same forces which formed the synclines and anticlines in the more massive underlying beds. The sub-angular appearance of the fragments argues for a submergence and prompt recementation of the broken beds.

If the thickness of D is anywhere near the 2,800 feet assigned to it by Logan, deposition must have been interrupted many times in the course of formation. The entire thickness is strikingly thin bedded wherever bedding planes have not been obliterated by subsequent folding and recementation.

SIMILARITY OF PHILIPSBURG AND EAST SHOREHAM SECTION

Brainerd and Seely divided the Beekmantown rocks exposed at East Shoreham, Vermont as follows:[1]

DIVISION E

Fine-grained magnesian limestone in beds one or two feet in thickness, weathering drab, yellowish or brown. Occasionally pure limestone layers occur, which are fossiliferous, and rarely thin layers of slate.

Thickness.....470 ft.

DIVISION D

4. Blue limestone in thin beds, separated from each other by very thin tough slaty layers, whose weathered edges protrude in undulating lines. The limestone often appears to be a conglomerate, the small enclosed pebbles being somewhat angular and arenaceous. (100 ft.)

3. Sandy limestone in thin beds, weathering on the edges in horizontal ridges one or two inches apart, giving to the escarpments a peculiar banded appearance. A few thin beds of limestone are interstratified with the siliceous limestone. (120 ft.)

2. Drab and brown magnesian limestone, containing several beds of tough limestone toward the middle. (75 ft.)

1. Blue limestone in beds one to two feet thick, breaking with a flinty fracture; often with considerable dolomitic matter intermixed, giving the weathered surface a rough, curdled appearance; becoming more and more interstratified with calciferous sandstone in thin layers, which frequently weather to a friable ochreous rotten-stone. (80 ft.)

Thickness.....375 ft.

DIVISION C

4. Magnesian limestone like No. 2, frequently containing patches of black chert (120 ft.)

3. Sandstones, sometimes pure and firm, but usually calciferous or dolomitic (70 ft.)

2. Magnesian limestone in thick beds, weathering drab. (100 ft.)

1. Grey, thin-bedded, fine-grained, calciferous sandstone, on the edges often weathering in fine lines, forty or fifty to the inch, and resembling close-grained wood. Weathered fragments are frequently riddled with small holes, called Scolithus minutus by Mr. Wing. (60 ft.)

Thickness.....350 ft.

DIVISION B

Dove colored limestone, intermingled with light grey dolomite, in massive beds; in some places for a thickness of twelve or fifteen feet no planes of

[1] Brainerd and Seely, *Bull. Am. Mus. Nat. Hist.*, Vol. III, 1890–91.

stratification are discernible. In the lower beds, and in those just above the middle the dolomite predominates; the middle and upper beds are nearly pure limestone; other beds show on their weathered surface raised reticulating lines of grey dolomite.

Thickness.....295 ft.

DIVISION A

Dark iron grey magnesian limestone, usually in beds one or two feet in thickness, more or less siliceous, in some beds even approaching a sandstone. Nodules of white quartz are frequently seen in the upper layers and near the top, large irregular masses of black chert, which, when the calcareous matter is dissolved out by a long exposure, often appears fibrous or scoriaceous.

Thickness.....310 ft.

Total thickness of section.....1,800 ft.

This section is perhaps the best known and most complete exposure of Beekmantown rock in the western part of the Champlain Valley. Certain faunal and lithological zones, well-marked in this section, are clearly present in the Philipsburg section, sufficient, it is believed, for exact correlations. These correlations appear to obtain throughout the Champlain Valley whenever good sections of Beekmantown strata occur. In view of this fact, it would seem that the term Beekmantown should no longer be used in a vague, indefinite sense, pertaining in general to any strata above the Potsdam and below the unconformity at the base of the Chazy. It is the opinion of the writer that the terms Lower, Middle and Upper Beekmantown, can be used in a definite, formational sense, and he therefore proposes those names for the Beekmantown in the Champlain Valley, to be applied in the following manner.

LOWER BEEKMANTOWN

Unfortunately the lower part of the Philipsburg section is cut off by a fault, while that of the East Shoreham section rests in uncertain relationship on the underlying so-called Potsdam sandstone. Nevertheless it is apparent that Brainerd and Seely's Divisions A, B, and C at East Shoreham are lithologically similar to Logan's Divisions A_1, A_2, A_3 at Philipsburg. Dark iron grey magnesian limestone, usually in beds one or two feet in thickness, more or less siliceous, in some beds even approaching a sandstone, characterize the lowest members of both sections. Nodules of

white quartz are frequently seen in the upper layers of A at East Shoreham and A1 at Philipsburg. Near the top of this member at both localities, large irregular masses of impure black chert occur. The most striking similarity in the two members is the apparently complete lack of fossil remains. The thicknesses given for the respective members are 310 feet and 400 feet. The former probably represents the entire thickness at East Shoreham. Logan's estimate, on the other hand, cannot give indication of the true thickness because of the overthrust fault cutting off the base of the section at Philipsburg, and because of faulting and close folding which probably occur down the dip of the member, but which are not clearly shown in available outcrops. It is probable, however, that the Beekmantown strata thicken to the northeast.

Overlying the lower zone in both the eastern and western territory is pure, predominantly dove-colored limestone. The thickness for this bed is given as 295 feet at East Shoreham. This estimate includes transition beds above and below, which are dolomitic. The middle, however, is nearly pure limestone, and therefore a distinct horizon in a section that is largely dolomite. This bed is represented at Philipsburg by Logan's Division A2, estimated at 100 feet and lithologically identical with the pure limestone facies of the middle of Division B at East Shoreham. In both sections the Lower Beekmantown is terminated by a series of red-grey to black dolomites, magnesian limestones and sandstones from 200 to 350 feet in thickness.

The uppermost members of the Lower Beekmantown on both eastern and western shores of Lake Champlain are, like the lower members, quite devoid of fossils. It is interesting to note that the only fossils reported from either region were derived from the middle, pure grey limestone horizon; at East Shoreham *Orthoceras primigenium Vanux.*, *Cryptozoön steeli*, and an indeterminate gastropod of the Holopea type; and at Philipsburg, indistinct forms resembling the genera *Pleurotomaria* and *Holopea* have been observed. Although it would be dangerous to draw conclusions concerning the exact age of these lower members on such a scant faunal basis, it is true that what fossils do occur are prophetic of a later Ordovician fauna and not reminiscent of any known Upper Cambrian forms.

In 1910, Ulrich and Cushing[1] in studying the age and relations of the Little Falls dolomite, which they correlate with Division A and the part of B below the dove-grey limestone horizon at East Shoreham, found evidence of an important break between the Little Falls dolomite and the Tribes Hill limestone above. Commencing at Ticonderoga on Lake Champlain and passing from there to Whitehall, 20 miles south, thence to Saratoga, 35 miles farther south-southwest from Whitehall, thence into the Mohawk valley, 20 miles southwest of Saratoga, and from there west to Little Falls, Middleville, and Newport, about 40 miles farther, they found evidence of this important unconformity. They state that the Tribes Hill and Little Falls formations seem unconformable everywhere in New York and they make this unconformity the dividing line between the proposed Ozarkic and the Beekmantown.

Since the Division A and B at East Shoreham, which Ulrich and Cushing have correlated with the New York Little Falls dolomite and Tribes Hill limestone respectively, can be correlated so closely on lithological grounds with Logan's Division A1 and A2 at Philipsburg, an unconformity might be expected between these two members. It is true that an abrupt change in the deposition did occur, but there appears to be no evidence of a diastrophic movement of importance. It is the opinion of the writer that the line between the Upper Cambrian and the Beekmantown in the Champlain Valley cannot as yet be definitely drawn. With more careful study of available sections, it becomes clearer that no important break occurred until the end of the Beekmantown. It is generally agreed that the stratigraphic relations of the Potsdam to the overlying Theresa and Little Falls dolomite indicate a sequence of sedimentation interrupted by no important break.

Wherever the line is drawn in the Champlain Valley, it does not seem logical on any ground to separate the Little Falls dolomite (Division A1) from the pure dove-colored limestone of Division A2 (Tribes Hill) at Philipsburg. Although faunal evidence is almost entirely lacking, it is apparent that the dolomites above and below the Tribes Hill limestone were deposited under essentially

[1] E. O. Ulrich and H. P. Cushing, *New York State Mus., Bull. 140* (1910), pp. 97–140.

the same conditions and separated from the Tribes Hill by no time break that could have greater than diastemic value.

The transition beds of Logan's A_3 at Philipsburg, made up largely of reddish grey, brown weathering dolomites, succeeded by black massive dolomites, appear quite unfossiliferous. They are clearly represented at East Shoreham by Division C of Brainerd and Seely. In both the localities these beds are characterized by large quantities of wind blown sand and by an absence of fossils. In both localities, dark massive dolomites predominate at the top. Above these massive dolomites in both regions come rocks that carry diagnostic fossils and it is here that the line should be drawn between the Lower and Middle Beekmantown. In this brief discussion of the lower Beekmantown, it has not been the writer's intention to lay down any definite limitations. The present state of knowledge concerning these unfossiliferous and deformed rocks is still too incomplete to warrant a final correlation at this time. It has merely been the intention to point out the possibility of correlating the Lower Beekmantown east and west of the great Champlain fault and to suggest the inadvisability of inferring a great unconformity between the Philipsburg representatives of the Little Falls dolomite and the Tribes Hill limestone. Until fossils are found directly above and below the contact between Logan's Division A_1 and A_2 that prove a considerable break, the pure limestone of A_2 must be considered to have been deposited, to be sure under special conditions, but in the same sea without intervening erosion directly subsequent to the formation of the impure dolomites of Division A_1.

MIDDLE BEEKMANTOWN

The Middle Beekmantown at East Shoreham, Vermont, in which the writer proposes to include Brainerd and Seely's Divisions D_1, D_2, D_3, D_4, and E, rest with apparent structural conformity on the Lower Beekmantown. These Divisions can be correlated with the Middle Beekmantown at Philipsburg which includes Logan's Divisions B_1, 2, 3, 4, and 5, and C_1, on faunal and lithological grounds. Divisions B_5 (upper part) and C_1 are not represented at East Shoreham because of post-Beekmantown erosion, which removed all of the uppermost strata of the Middle Beekman-

town in this region. Here the Lower Chazy rests upon Division E, which is poorly represented but can be correlated with the lower part of Division B5 at Philipsburg. It is proposed here to include in the Middle Beekmantown all the strata predominantly of massive limestone and dolomite above the transition beds of the Lower Beekmantown, and below the shale and limestone conglomerate beds of the Upper Beekmantown. The advent of the Middle Beekmantown according to this division is sharply marked by the appearance of Ophileta complanata, and the close is equally sharply marked by the occurrence of a typical gastropod and cephalopod fauna. Like the Lower Beekmantown, the Middle is predominantly calcareous and dolomitic, while the Upper is characteristically shaly. It is perhaps not necessary here to enter upon a detailed comparison of the fauna of the Middle Beekmantown but merely to note the presence of a fauna assemblage in Divisions D5 and C1 at Philipsburg which is very similar to that found at the top of D1 at East Shoreham and known as the "Fort Cassin fauna." This marked zone of gastropods and cephalopods can serve as a general indication of the top of the Middle Beekmantown. Occupying approximately the same horizon in both localities and being dominated by thick-shelled representatives of such genera as *Murchisonia*, *Holopea*, *Cyrtoceras*, *Ecculiomphalus*, *Maclurea*, *Euomphalus*, *Raphistoma*, *Lophospira*, and *Orthoceras*, there is a marked similarity generically between specimens from the two provinces. Lithologically also the rocks are quite similar.

UPPER BEEKMANTOWN

It is proposed to include in the Upper Beekmantown all strata between the massive beds carrying the Fort Cassin fauna and the Chazy unconformity. In the Philipsburg region this consists of an unknown thickness of closely folded slate with intercallated lenses of limestone conglomerate. Near Mystic Station in one of these conglomerate outcrops, a fauna was collected by the writer which differed markedly from the typical Upper Beekmantown fauna of this region. It is possible that the Normanskill has been infolded at this locality. The Upper Beekmantown must, of necessity, be indefinite because of the erosion which followed its deposi-

tion. With the exception of the rocks at Stanbridge, it is not known to be represented in the Champlain Valley.

OTHER EXPOSURES OF BEEKMANTOWN IN THE CHAMPLAIN VALLEY

In a section at Fort Ticonderoga, New York, Brainerd and Seely report the presence of 75 feet of limestone with *Ophileta complanata* which they correlate with their Division D1. They report the presence of Division E with several undetermined species of *Euomphalus*, *Lituites*, *Cyrtoceras*, and *Orthoceras*. The strata between the top and bottom of the Middle Beekmantown are apparently unexposed here.

At Thompson's Point, 28 miles north of Fort Ticonderoga, Beekmantown strata occur, which probably belong to the Lower and Middle divisions.

At Providence Island, 24 miles north of Thompson's Point, New York, 236 feet of largely magnesium limestone occurs which probably belongs to the upper Middle Beekmantown.

The type section one-half mile north of Beekmantown station is very poorly exposed but carries the gastropod and cephalopod fauna which appears to mark the upper Middle Beekmantown.

Keith has recently brought to attention two formations from northern Vermont which may have close relationship with the Philipsburg strata to the north.[1] Three miles N.E. of Burlington occurs the Shelburne marble of 200 feet or more in thickness, which occupies the same stratigraphic position as the Highgate slate to the north. The Highgate slate has yielded fossils which Walcott and Schuchert have determined as Upper Cambrian. It is believed that the Shelburne marble is younger than the Highgate slate, and that the disappearance of the Highgate southward was more likely due to Upper Cambrian erosion than to non-deposition. The formation is almost entirely of white marble and may be contemporeaneous with the lowest beds (B1) of the Middle Beekmantown at Philipsburg, which have a similar marbleized facies.

The next succeeding formation described by Keith is the Williston limestone, which also outcrops near the town of Burlington.

[1] Arthur Keith, *Am. Jour. of Sci.*, Vol. V (1923), pp. 97–139.

This formation consists of light or dark blue limestone and marbleized quartzite and also dolomitic limestone. The prevailing blue color and thin bedding distinguishes it from the Shelburne. Fossils, although scarce, have been found. Some cephalopods and Ophileta-like gastropods were collected by Schuchert who assigned them to the "Saratogan." It is possible that this formation can be correlated with B_2 and B_3 at Philipsburg. The presence here of the trilobite *Lloydia saffordi*, which is highly characteristic of the Middle Beekmantown at Philipsburg, makes such correlation seem very plausible.

CONCLUSIONS

The purpose of this study of the Philipsburg section was to gain new knowledge concerning conditions during early Ordovician times. Although the fossil evidence to prove that the rocks of Division A belong to the same system as those of the overlying series is scant, nevertheless it at least in a small degree supports the testimony of field evidence. The field evidence indicates that no great break occurs until the end of the Beekmantown. It seems, therefore, just as logical to include the rocks of Division A with the Lower Beekmantown as to throw them into an older system for which, at least in this locality, there is no favoring evidence, either faunal or diastrophic. The divisions of the Beekmantown into Lower, Middle, and Upper, proposed in this paper, are believed by the writer to obtain generally in the Champlain Valley. To carry these correlations further is not advisable at this time because of the insufficiency of our knowledge.

FOLDS RESULTING FROM VERTICALLY ACTING FORCES[1]

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Because the most striking examples of folded rocks are to be seen in mountainous regions, folds are usually thought of as the visible results of compressional forces which act more or less parallel with the surface of the earth, the typical force of this kind being the compression effect of differential contraction of the lithosphere. But with the rapidly accumulating knowledge of more stable areas of the present land surface and especially from the increasing mass of data from deep well records, the importance of another kind of fold has come to be recognized. Although it seldom affects the present topography directly, this kind of fold is of great economic value because of its influence on the distribution and accumulation of gas, oil, and brines. Some of these folds are actually the direct result of a force acting vertically, others which also owe their origin to a vertical force seem to be rather the effect produced by components of this force acting more or less parallel with the beds. Most of the folds due to vertical forces occupy circular or oval areas, either singly or as groups. This shape or arrangement indicates an apical area which has been directly affected by an up-thrust or a down-throw.

At least five types may be recognized: domes or quaquaversal folds, radial linear folds, concentric terrace folds, linear terrace folds and monoclinal folds related to deep-seated faulting. Of these only one class, the domes or quaquaversal folds, is typically due to a force acting upward. As one would expect from the theoretical conception of the earth as a failing structure, most of the forces acted downward.

[1] Published with the consent of the State Geologist.

DOMES

These are the conspicuous folds resulting from an upward acting force, or from a set of forces whose resultant is active upward; as such they have been described for many years. They are often found to be genetically related to a bathylith, laccolith, or lava plug, but sometimes they are merely the locus of chemical action or of recrystallization which results in a great increase of volume within a limited area, as may be the case in the salt domes of the Gulf states whose origin is imperfectly understood. Less frequently, slight domes arise from the slumping of soft sediments. This is a phenomenon noted at times in present-day accumulations. Others are found in areas of different compressibility in the same layers of rock, especially near shore lines. How much difference in elevation the subsequent rock pressure might bring about upon such areas of unequal compressibility, cannot be estimated with the incomplete data at hand, but this may prove to be an important factor. In size, domes vary from great groups of mountains to small inconspicuous rises of ground a few acres in area.

RADIAL LINEAR FOLDS

Small folds are found near the periphery of large basin structures with their axes pointing toward the center of the basin. They are so broad and shallow that they are seldom recognized except when the section is plotted with vertical exaggeration. The dip of the limbs of these folds as they are found in the Michigan basin is well within the limit of initial dip of sediments, and the pitch of the axes is roughly parallel with the dip of the series as a whole. These folds, if known only for a single formation, would be considered to be due to peculiar conditions of deposition, but from the fact that they persist through many formations, and appear at points on every quadrant of the basin, they are obviously structures formed after consolidation. The uniformity of their distribution and their dimensions favor the idea, which was first proposed by Professor I. C. Russell,[1] that they are a result of the subsidence of a central area resulting in a crinkling of the peripheral portion just as an unfolded filter paper crinkles when pressed into a funnel.

[1] *Mich. Geol. Surv. Pub. 12*, Geol. Ser. 9, p. 207

It may be noted that this sort of fold would be the most imperfect "structure" possible for accumulating light liquids and gases, because the pitch would be uniform from the point of inception of folding to the outcrop and would be equal to, or greater than, the dip of the series as a whole.

Another explanation of the origin of these folds is that they are the result of unequal subsidence of portions of the periphery of the basin, but this explanation is less satisfactory in the case of the Michigan folds because such subsidence would be expected to produce faulting and folds of widely varying dimensions and unequal distribution.

An unequal distribution of soluble material such as rock salt near the periphery and its removal by solution, or the unequal solution of parts of a salt horizon, have been suggested to account for these folds. Considering only that area in southeastern Michigan where both the folding and the salt beds are best known, this explanation seems most reasonable, but as the folds are also known from other parts of the basin where the presence or absence of salt beds of sufficient thickness to produce the subsidence effect has not been proved, this, with the other explanations, must be only tentatively considered until more data are at hand. Whichever of the above hypotheses is favored, it will be noticed that the underlying cause is a vertically acting force, although under the subsidence hypothesis first mentioned, the force is supposed to be resolved into components acting tangentially around the periphery.

An examination and platting of well records already assembled by Lane[1] and Smith[2] results in the following pertinent suggestions.

1. The folds affect the latest rocks which are preserved—the Mississippian and Pennsylvanian.

2. There is an indication of gentle monoclines or terraces around the central basin which suggests two periods of subsidence.

3. These terraces separate the comparatively deep central area from the shallower peripheral area, and thus are suggestive of two distinct diastrophic areas.

[1] *Mich. Geol. Surv.*, Vol. V, 1881–93.

[2] *Mich. Geol. Surv. Pub. 14*, Geol. Series 11.

On the accompanying structure contour map (Fig. 1) several of these folds are indicated, but these are perhaps not the most typical examples because they are folds of larger dimensions, and

FIG. 1.—Structure contour map of Michigan. Contours drawn to the top of the Dundee (Onondaga-Hamilton). Areal distribution of Dundee, in outcrop and beneath the drift, in solid black. Contour interval 100 feet.

a lack of data makes it impossible to use a contour interval which would reveal the smaller and more common folds. Perhaps the most typical example shown is that of the St. Clair area (*A*). The shape and orientation of the fold in the Saginaw area (*B*) are typical, but the position of this fold is exceptional in that it lies near the center of the basin. The smoothness and regularity of the contours in the northwestern part of the state are due to a lack of data from deep wells. However, folds of the radial linear type are known from surface observations in the Northern Peninsula in the northwest quadrant of the basin. The location of one of these folds is shown in Figure 2 which is drawn to show the theoretical direction and extent of the radial linear folds of the basin.

The Michigan basin is exceptional in its lack of distortion by tangential forces, and therefore has a more conspicuous development of these folds, but it is believed that such folds are a feature to be sought for in every basin of persistently negative tendency. It is conceivable that under some conditions such folds might indicate favorable areas for prospecting for oil and gas. In case of unconformity, and with impervious sedimentary beds deposited over such folds after the deformation but before any great migration of contained fluids, this would certainly be true.

CONCENTRIC TERRACE FOLDS

A basin of persistently negative tendency, in which the only movements are slight and long continued, would be expected to develop terraces parallel to the margins of the basin and concentric around the central area, especially in the parts of the basin which are bordered by elements of a positive tendency. Such terraces have developed in the Michigan basin in the southern part, bordering the positive area which has been influenced by the Cincinnati anticline. These terraces which are shown in Figure 1 are found, by a comparative study of well records, to be developed at least as far down in the stratigraphic column as the Dundee (Onondaga-Hamilton). Such structures are important economically, and the significance of an understanding of their mode of origin and typical arrangement in regard to negative and positive areas, will be at once obvious to petroleum geologists.

FIG. 2.—The direction of the axes of folds as indicated by the results of deep drilling. Adapted from R. A. Smith.

LINEAR TERRACE FOLDS AND MONOCLINES BY FAULTING

These folds which exhibit similar features, and are well known from their development as oil producing areas, differ only in their

mode of origin. The linear terrace folds result from long continued gentle movements, and the monoclines produced by faulting are the expression of deep-seated faults which have decreased in effect toward the surface until, in the upper layers, there is distortion of the beds without actual rupture.

DEFINITIONS AND CONCLUSIONS

Domes or quaquaversal folds.—A. Inconspicuous folds usually small formed in undisturbed areas; the force secondary and small, vertical. The force may be (*a*) a chemical action or crystallization (salt domes), (*b*) the vertical component of lateral thrusts set up within the sediments, still soft, by the sudden accumulation of heavy sediments shoreward,[1] or (*c*) the unequal contraction during induration of sediments of differing compressibility. No topographic expression.

B. Conspicuous folds often large, the force coming from movements of magma. Domed mountains above bathyliths, laccoliths, lava plugs. Topographically striking.

Radial linear folds.—Small, radial, about basins of slight negative tendency; become apparent through drill records; dip of limbs well within the limit of initial dip; distinguished from folds due to unequal contraction during induration only by radial arrangement and persistence of fold to the basin floor contemporaneous with subsidence. Dominating force vertical and downward with resultants tangential in concentric areas giving compression effect parallel to periphery of basin.

Other explanations: unequal subsidence which would be more likely to cause faulting; unequal distribution or unequal solution in evenly distributed, easily soluble material such as salt.

Concentric terrace folds.—About basins of negative tendency. Caused by a failure of concentric areas, or by differences in compressibility of sediments. Simulate terraces due to thinning of sediments toward center of basin. Known only from comparison of deep borings. No topographic expression.

[1] See M. Albertson, *Mining and Metallurgy*, No. 170 (February, 1921), p. 38.

Linear terrace folds.—On long lines of movement in some cases apparent at surface. Not due to concealed faulting. Seldom have topographic expression.

Monoclines by faulting.—Simple monoclinal folds due to concealed faults. In some cases, with topographic expression.

This article has been written with the purpose of directing attention to the importance, economically, of the structures described. In the Michigan basin little encouragement is offered for their exploration, chiefly on account of the long continued exposure of this area to erosional forces, continuing as it apparently did from Pennsylvanian to Pleistocene time, thus keeping open the path for the escape of fluids along the axes of the radial linear folds and preventing the deposition of any impervious layers above them but with a different Tertiary or Mesozoic history areas of a similar nature would offer many interesting possibilities.

A PALEOZOIC ANGIOSPERM

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The morphology of Paleozoic plants is based for the most part upon the microscopic examination of concretions found in English, French, and German coal seams. These concretions are calcareous in England, and siliceous in France and Germany, and contain well-preserved tissues of plants. The matrix can be cut with a diamond saw, and the sections ground to transparency. The concretions are black, round, or irregular lumps, varying in size from an English walnut to a cocoanut. They appear in the upper part of the coal seam but never outside of it. In England they are called coal-balls and in Germany Torfdolomiten. The French use the English word. The value of a coal-ball for morphologic plant study depends not only upon the vegetable contents but also upon its purity from pyrite. The latter does little harm if it occurs in very small quantities, but observations are made impossible if the replacement of calcite or silica has progressed too far.

A great service to science, in making micropreparations from English coal-balls, has been rendered by the Lancashire and Ceshire Coal Research Association, better known as the Lomax Palaeo-Botanical laboratories of Bolton, England. There a wonderful technique has been developed by Mr. Joseph R. Lomax, who prepared the material for the classic investigations of W. C. Williamson, D. H. Scott, A. C. Seward, R. Kidston, F. W. Oliver, A. J. Maslen, and M. Benson. Almost all paleobotanic micropreparations in England and North America were supplied by the Lomax laboratories.

It seemed obvious that coal-balls should also be found in the extensive American coal basins, and a thorough search was made for them. The writer has collected good specimens in Illinois and Kentucky, and others were sent to him from Texas. It is true that

pure balls which contain only negligible quantities of pyrite are rare, but one collected by the Illinois State Geological Survey at Harrisburg, Illinois, O'Gara Mine Number 9, coal seam Number 5, satisfied all reasonable demands for purity. It was sectioned by Mr. J. H. Hoskins, of the Department of Botany at the University of Chicago, and described by him.[1]

The coal-ball in question contained an angiospermic stem of distinct monocotyledonous affinity. The stem portion was about 4 cm. long and 2 cm. in diameter. Throughout the cross-section (Fig. 1) are scattered numerous endarch collateral vascular bundles.

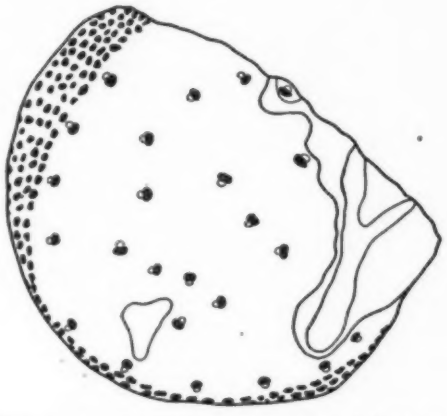

FIG. 1.—Diagram of cross-section of stem with peripheral groups of sclerenchymatous cells and scattered collateral bundles; xylem shown in black; rootlet has penetrated one side of stem (after Hoskins).

The phloem is oriented toward the periphery. The detail of a single bundle with phloem preserved is shown in Figure 2. Surrounding the xylem is a sheath of sclerenchymatous fibers, not extending completely around the bundle, nor present at the phloem side. Between this sheath and the heavy-walled xylem cells are usually thin-walled parenchyma. Throughout the cross-section are what were probably mucilage ducts. Placed near the periphery of the

[1] J. H. Hoskins, "A Paleozoic Angiosperm from an American Coal-ball," *Botanical Gazette*, Vol. LXXV (1923), pp. 390–97.

stem are numerous groups of small hexagonal and thick-walled sclerenchymatous cells, arranged in four or five irregular concentric rows. All these elements are surrounded by the solid parenchymatous tissue of the stem. The phloem was not preserved in most cases, but figure 2 shows it consisting entirely of thin-walled cells arranged

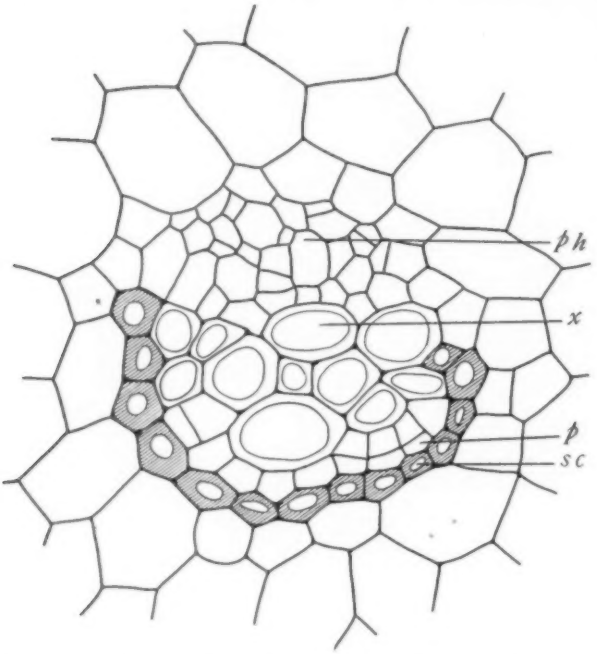

FIG. 2.—Cross-section of vascular bundle: *sc*, sheath; *x*, xylem; *ph*, phloem; *p*, parenchyma; ×350 (after Hoskins).

in such a way as to suggest large sieve tubes with companion cells. These morphological characters warrant the conclusion that the stem belonged to an angiospermic plant of the Monocotyledon branch. Although a comparative study with certain living Monocotyledons brings out striking similarities, a more definite statement as to the phylogenetic position of the fossil is postponed until other material can be secured. Therefore the generalized name "Angio-

spermophyton americanum" was chosen for the first-known Paleozoic plant of angiospermic affinity.

No traces of Angiosperms have previously been known below the Comanchian. Our coal-ball carries the highest plant type a long way back in the geologic time scale. Does it mean that we must greatly modify our conceptions of plant evolution? By no means. Only the lines of descent which seemed to converge in the Mesozoic take an aspect of greater parallelism which presupposes an immensely removed focus, just as the sun beams appear parallel to our eye and yet we know of their convergence. Succeeding discoveries in the geologic history of plants and animals convince us more and more of the long duration of the unrecorded stage of evolution.

COMMUNICATION

To the Editor:

The comparison of shapes of valleys to capital letters of the alphabet —U for glaciated valleys and V for those due to ordinary river erosion has long been used quite helpfully in textbooks of physiography. I have found a few other letters of the alphabet helpful in the same connection. I submit them to you and to other teachers for suggestion and criticism:

I-shaped valleys—extremely young, of the cañon type, corrasion very rapid with relation to lateral weathering;

V-shaped valleys due to river erosion, width of V dependent on the ratio of weathering to corrosion;

Y-shaped valleys—rejuvenated, the grade of the river has been recently increased by uplift or uptilting of the head waters;

W-shaped valleys—the river acting as a distributary in a flood plain which is highest near the river, grade of the river therefor decreasing either by uptilting of the mouth or down tilting of the head waters, or otherwise. The application of the letter W to this form of valley is something of a stretch, yet I find it well worth while to emphasize the fact that such streams as the Mississippi and the Poe have as the highest part of the flood plain that immediately near the river, so that a cross-section of their valleys has more the shape of a cross-section of a plate or pan. In fact I have used the term pan-shaped for these sections. But it is schematically desirable to use another letter, and W lends itself fairly well. U-shaped valleys remain as usual glaciated valleys.

ALFRED C. LANE

REVIEWS

The Foundry Sands of Minnesota. By G. N. KNAPP. *Bull. 18,* Minn. Geol. Survey, 1923, pp. 105. figs. 13, tables 17.

Foundry sand has been defined heretofore as a sand or loam which has the following properties: it must contain sufficient clay or other binding material to enable it to stand up in the mold; it must be sufficiently porous to allow steam and gases to escape, and must be sufficiently refractory to resist fusion. But precise measurement of any of these properties has rarely been attempted, and figures expressing these properties quantitatively are very meager, or wanting.

The purpose of the investigations described in this Bulletin was to place these properties on a quantitative basis. A careful measurement of each of the essential properties of molding sands was undertaken, and the absolute and relative values of the results are given in definite figures and percentages.

The clay content of various types of foundry sands was accurately determined by elutriation, and is given in percentages by weight. The bonding power of the elutriated clay was found to vary with the kind of clay, and this difference in bonding power was attributed to the probable variation in the amount of colloidal material present in clays of different types. The colloidal content was not determined.

The moisture content of sands in actual foundry practice was found to vary from 1.7 per cent to 12 per cent by weight, this variation being due to proportioning of the fine and coarser sizes in the sand, the clay content, and the kind of clay. The amount of colloidal material was probably also an important factor.

The mechanical analyses of the sands and loams were carried to a greater degree of refinement than heretofore. The laboratory work demonstrates that sizing of sands by screen sieves cannot be done accurately with the clay and silts present, because of the inevitable presence of clusters of fine grains, and the adhering of fine grains to the coarse ones. The silts are shown to play an important rôle in granulation, on which permeability in molded sands largely depends.

The permeability of the sands in the natural condition, as well as in the molded state, was determined by actual measurement which had

not previously been done. The permeability tests demonstrate that sand when moistened and rammed into a mold is usually from two to ten times as permeable as the same sand in a dry, disintegrated state, which shows the extent to which granulation is effective. The permeability tests serve also to emphasize what was inferred in advance, that the porosity of a sand in its natural state is no measure of, and not necessarily an index to the permeability, either in the natural state or after being molded. The permeability of the molded sand is a function of the structure developed, which in turn is largely a matter of granulation.

When the field work was done for this Bulletin in 1918, foundry sands and clays were being shipped in large quantities from distant localities in New York, Missouri, Illinois, Ohio, Kentucky, and Colorado. As a result of this investigation nearly all of the materials that were required in the foundries were found to occur in Minnesota.

Contributions to the Paleobotany of Peru, Bolivia and Chile. Five papers by EDWARD W. BERRY. "The Johns Hopkins University Studies in Geology," No. 4. Baltimore, 1922. Pp. 221, pls. 25, figs. 9.

The following five topics are treated in these papers: "Carboniferous Plants from Peru"; "The Mesozoic Flora of Peru"; "The Flora of the Concepcion-Arauco Coal Measures of Chile"; "Pliocene Fossil Plants from Eastern Bolivia"; "Late Tertiary Plants from Jancocata, Bolivia."

In his first paper, Berry examines the coal-bearing rocks south of the Port of Pisco on the peninsula of Paracas, which is about 220 km. south of Callao. He thinks that these deposits correspond to the Westphalian stage. His conclusions are based largely upon the fossil plants found in these deposits. The following genera are represented by rather common species: Palmatopteris, Eremopteris, Calamites, Calamostachys, Lepidodendron, Lepidophyllum, Lepidostrobus, Stigmaria, and Knorria.

Berry's second paper in this collection attempts to sum up our present knowledge of the Peruvian Mesozoic flora. Mesozoic rocks are very widespread in Peru, and are particularly prominent in the Cordillera Occidental, especially between latitudes 5° and 13° S. Most of the Jurassic and Cretaceous horizons are represented. A collection of fossil plants was made on the San Lorenzo Island. Berry gives a list of genera from the Mesozoic of Peru, all of which, with one excep-

tion, are represented in the English Wealden, and only one is found in the Potomac flora of Eastern United States.

The third paper deals with the Miocene flora in southern Chile, and with deposits which are of particular interest, because they represent the Tertiary coal fields of Chile. The genus Araucaria is very prominent in this flora, and Berry discusses at considerable length the Mesozoic and Tertiary distribution of Araucarias throughout the world, with reference also to the recent occurrence of this type. The floral elements of the Tertiary in Chile are compared with other fossil floras and present-day distribution of plants in South America.

The next paper deals with the Pliocene fossil plants from eastern Bolivia. The flora and its environmental conditions are discussed. Berry draws some conclusions as to the changes of level, in consequence of the uplift of the Andes Mountains, which has taken place since this flora existed. His conclusion is that the rise must have been not less than 6,500 nor more than 9,000 feet. The author includes a list of these plants which he calls the Pisllypampa flora.

The last paper deals with the late Tertiary plants from Jancocata, Bolivia. This flora, according to his determination, is of Plio-Pleistocene age.

The foregoing articles contain much valuable information on the climatological and ecological conditions under which these floras grew up. They are a valuable addition to our knowledge of South American fossil plants. But there is still a great deal to be done along these lines, although the departments of mines of the South American states seem to have been not unmindful of the interesting plant deposits in their respective countries.

A. C. N.

Rocks and Their Origins: By GRENVILLE A. J. COLE. Cambridge University Press, 1922. Pp. 175, figs. 20.

This little book, the first edition of which came out in 1912, is inscribed by the author as "intended for those who are not specialists in geology." A comparatively slight knowledge of geologic technology is presupposed on the part of the reader; and the style of the book is simple and clear, but the simple treatment does not entail any loss of accuracy of statement.

A brief introductory chapter brings out the distinction between rocks and minerals, and lists the more common minerals with their chemical compositions. A chapter each on limestones, clay rocks, sandstones, igneous rocks, and metamorphic rocks constitutes the remainder of the

volume. Each rock type is treated rather fully as to origin, varieties, alteration, and surface expression. The current conceptions of the different rock-forming processes are developed historically, the most important contributory theories, past and present, being discussed in each case. It might be said that this is done too fully for an elementary book; but, on the other hand, the critical background which this presentation gives the reader is valuable, and will make the book of interest to many geologists.

The extensive illustrations used to bring out different points are interesting and effective, and are chiefly drawn from Europe and other parts of the Eastern Hemisphere, thus being fresh to many Americans.

T. B. R.